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Non-stationary 3D Perturbation Theory for Describing Nonlinear Interaction of Electric Field with Matter in Inhomogeneous Plasma with Current. Vysikaylo's Electric Field Shock Waves and Plasma Nozzles

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Abstract

In our works we theoretically prove that the cumulation (self-focusing) of charged particles in a inhomogeneous plasma (with current) is a universal property of cumulative-dissipative structures with characteristic sizes from 10^{-15} to 10^{26} m. Electrical phenomena are observed in non-uniform atmospheres and ionospheres of all planets of the Solar System. In this paper, the most complete theory of perturbations to describe phenomena in gas discharge plasma is formulated and, based on this theory, the most complete classification of ambipolar transfer processes in plasma with current and the classification of non-uniform plasma parameter profiles are given. We compare our theoretical results with existing experiments and results obtained in other areas of the natural sciences. In this work, we theoretically (Part 6.1) and experimentally (Part 6.2) we prove that shock waves of electric fields are focusing shells for inhomogeneous plasma cumulative-dissipative positively charged 3D structures. In the Part 6.1 of this work, we provide detailed theoretical justifications for the possibility of the existence of (locally self-focusing by ambipolar drift) Vysikaylo's electric field shock waves caused by ambipolar diffusion due to a violation of the electrical neutrality of the plasma (in the presence of an electric current). Due to the greater mobility of electrons (ions are more massive), a structure with a positive space charge is formed in the electric field shock waves that self-form in the plasma (with current). Unlike Mach's shock waves, in closed Vysikaylo's shock waves transverse electric fields are generated due to the space charge. This makes the problem (in the electric field shock wave region) three-dimensional (in particular, spherically or cylindrical symmetric in this region). In Part 6.1, we will limit ourselves to the study of stationary one-dimensional profiles: 1) parameters in shock waves of the electric field and 2) processes of ambipolar drift, leading to local cumulation of positive charge in the shock wave of the electric field. In Part 6.1, the author will limit himself to obvious remarks arising from the properties of three-dimensional structures with a positive space charge. Based on laboratory 3D experiments (Part 6.2) and theoretical studies of gas-discharge plasma, we prove that ambipolar drift caused by different dependences of the mobility of electrons and positive ions in a simple plasma (with one type of ions) determines the dynamic processes of cumulation of plasma structures – 4D plasmoids in plasma (with current). 4D plasma structures are non-stationary three-dimensional structures. The author draws attention to self-formation in plasma structures (plasmoids) of stationary Vysikaylo's plasma nozzles - analogues of Laval's nozzles. A comparison of theoretical 1D and experimental 3D observations of discharge glow (this corresponds to changes in the main parameters) in gas discharge tubes will be presented in Part 6.2. In these experiments, a homogeneous plasma in a gas discharge tube is locally disturbed by a beam of fast electrons. This leads to the self-formation: 1) of electric field shock waves (a layer of positive volume charge) stopped by gas pumping and 2) of transition 3D profiles and Vysikaylo's plasma 3D nozzles already in a quasi-neutral inhomogeneous plasma. In this work, we were the first to theoretically and experimentally study the processes of nonlinear ambipolar transport caused by the violation of electrical neutrality and 3D interaction of electric fields with matter (charged particles) in an inhomogeneous plasma with current. For the first time it has been proven that the coefficients of ambipolar diffusion due to the violation of electroneutrality are vectors determined by the electric field vector.

Keywords: Ambipolar Diffusion, Perturbation Theory, Weak Violation of Electrical Neutrality, Inhomogeneity of the Electric Field Ambipolar Transport, Ambipolar Drift, Ionization Waves

1. Introduction

Magnets and magnetism have been known since ancient times, with the study of the magnetic field beginning in 1269, when the French scientist Peter Peregrinus (Knight Pierre of Méricourt) used steel needles to plot the magnetic field on the surface of a spherical magnet and found that the resulting magnetic field lines intersected at two points, which he called "poles" (by analogy with the poles of the Earth). Almost three centuries later, William Gilbert of Colchester used Peter Peregrinus' work to state for the first time definitively that the Earth itself was a magnet. Gilbert's work "De Magnete", published in 1600, laid the foundations for magnetism as a science.

The study of electric fields began with the discovery of Coulomb forces by Coulomb in 1785. Despite the parameter v/c (v is the speed of charged particles, c is the speed of light), electric fields continue to be ignored in astrophysics and ionospheric physics and only magnetic forces are taken into account. In this paper, the main attention is paid to the features of the influence of internal electric fields on the formation of Vysikaylo cumulative-dissipative structures in inhomogeneous plasma with current. Such structures with pulsations and inhomogeneity of electric fields occur from 10-15 m to the size of galaxies and their clusters - 10^{26} m [1].

Here we will focus on the study of such structures in laboratory gas-discharge plasma. Electrons are more mobile than ions due to the smallness of their mass compared to ions. The electrons leave the plasma structures faster than positive ions and thereby charge them with a positive charge, the electric field of which returns a part of the low-energy electrons back to plasma structures. This is how dual (bound, entangled) flows of charged particles arise in the region of charged plasma structures. Reverse electron flows focus (cumulate) plasma dissipative structures. This is how cumulative-dissipative structures (CDS) with dynamic surface and volume tension appear and develop. There are structures with three types of cumulation of electrons (Fig.1a): with planar, spherical and cylindrical symmetries. When the activation energy of the medium is low, strata appear first. They focus weakly energetic electrons, some of which gain energy in the stratum and, further accelerated by the electric field, carry out an effective current transfer. As the energy increases, spherically symmetrical structures with dual cumulative jets (bi-cumulation of electrons and positive ions) are formed in the medium (Fig.1b, c). Then cylindrical symmetrical electric arcs and lightning bolts with cumulative stings are formed on these jets (jets of runaway electrons ahead of lightning were experimentally detected by B.F.J. Schonland in 1934-1938). Thus, when linear lightning is formed as a cumulative-dissipative structure, the local air conductivity increases by 10^{15} times. In an activated environment, it is possible to co-organize CDS with different types of symmetry (Fig.1a). The presence of a positive charge in the plasma structure leads to the formation of a flow of positive ions from the structure. The discovery of positively charged CDS with dual electron flows and with different types of symmetry in plasma was carried out in [2]. The idea in [2] was the possibility of co-organizing cumulating and dissipating energy, momentum and mass of opposite or orthogonal flows into a single self-organizing, in particular 8D dimensional, dual structure. The electric field strength acts in plasma as an additional and most important component that controls the behavior of all (except high-energy) charged plasma particles [2]. The electric field strength – E is always a vector and three-dimensional quantity that can change over time. Because of the internal electric fields, "a system of charged particles is essentially not a gas, but some completely unique system, pulled together by distant forces" [3]. Far Coulomb forces form: 1) potential mirrors focusing and reflecting charged particles; 2) separating the flows of charged particles into opposite ones (high-energy and low-energy, unable to leave the potential wells).

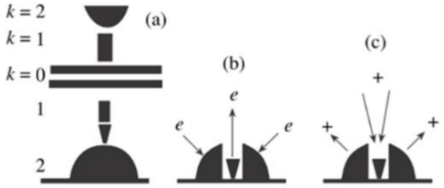

Figure 1: Examples of CDS with different symmetry [2]: (a) a possible arrangement of structured plasmoids with different symmetries. There is $k = 0$ correspond to planar (strata in a gas discharge), k = 1 to cylindrical (electric arcs, linear lightning), and k = 2 to spherical symmetry (cathode and anode spots). (b) Arrows indicate the directions of cumulation of electron flows and of the reduced electric field – E/N in the area of the cathode spot. Electrons – e appear in the bulk in the spot region, for example, due to UV preionization. (c) Corresponding diagram of cumulation of ion flows to the cathode spot.

The aim of the work is to carry out a more correct, account for the electric field strength – E. We will do this description of plasma using perturbation theory [4]. We will describe the phenomena of cumulative (mainly drift) and dissipative (mainly diffusion) transport controlled by internal electric fields. These phenomena lead to the formation of CDS of the following type: running and standing strata (known to Faraday); the effect discovered by Pekarik when the group velocity of the strata is opposite to the phase velocity; cathode spots; electric field shock waves discovered by Vysikaylo in gas-discharge plasma with current and visualized by him and his co-authors in gas-discharge plasma in a tube; plasma tails behind meteoroids; jets; sprites; elves; ordinary and beaded lightning (Fig.2,3), electric arcs and other plasma CDS [4]. The synergistic (joint, internal) field of uncompensated ions has a more significant effect on the behavior of electrons. It heats them, localizes weakly energetic electrons in positively charged potential wells, forms cumulation points L_1 between positively charged regions (Fig.2), forms cumulative jets of high-energy electrons from positively charged structures such as cathode positively charged spots into a positively charged plasma column [2,5], electric arcs or various lightnings. Without the presence of a positively charged cathode spot, the discharge current is negligible [6,7]. The shape of the cathode positively charged spot has an elliptical shape [7]. The cathode spot with its positive charge cumulates weakly energetic electrons to its center and throws them in the form of a cumulative jet into the region of the Faraday dark space (Fig.1b,c) [2,4]. Taking into account the positive charge of the cathode spot and the cumulation of low-energy electrons to its center explains the reverse movement of cathode spots in transverse magnetic fields, an effect experimentally established by Stark in 1903 [2]. Electrons, ionizing neutral gas particles, form ion concentration profiles; when atoms and molecules are excited, they form plasma glow profiles indicating possible profiles of the *E/N* parameter, reaching breakdown values, etc. There are currently two main approaches to describing the mechanisms of CDS generation.

The first approach is based on the study of the mechanisms of instabilities, i.e., an unlimited growth in time of the concentrations of discharge plasma particles. Within the framework of the first approach, it is believed that if a mechanism for an unlimited increase in plasma concentrations is proposed, then this will necessarily lead to radial (3D) pinching of a homogeneous discharge [8]. Here, the complex 4D Cauchy-Dirichlet problem is replaced by the 1D Cauchy problem in time, while the duality of electron flows into and out of the structure is not taken into account at all. This is mistake! Asymmetric hydrodynamic elliptical and other structures, with a pulsating electric field in space and Vysikaylo-Euler' libration points, shown in Fig.2, are "mysterious" for supporters of the first concept. Theorists have been trying to describe plasma structuring (strata) without involving a space charge for many years [9]. However, they have not yet been able to achieve satisfactory agreement between the results of numerical calculations and experiments with sharp drops in luminosity between strata [9]. Strata exist in discharges at pressure 15 torr and a discharge time of ~10 ns [10]. At these times, any processes of ambipolar diffusion are insignificant [4,5].

The second approach developed by us [2,4,5] is based on the search and study of dual (8D) processes of transfer and modification in 4D space-time of internal electric fields, leading to local cumulation of a previously homogeneous discharge. According to the second approach, the processes that form the CDS proceed simultaneously in opposite directions: from the CDS and to the CDS. Electron flows in CDS focus these structures and form dynamic surface tension in potential Coulomb wells. This leads to self-focusing of the volume positive charge in the CDS, i.e. to the processes of 3D cumulation of positive volume charge and internal electric fields. The cumulation of flows of charged particles and electric field strength leads to increased luminescence of the surface of plasma CDS (Fig.2 and 3). Focusing low-energy electrons exchange energy during Coulomb collisions, which leads to the processes of maxwellization of the electron distribution function and the constant formation of fluxes of high-energy runaway (from plasma CDS) electrons. It is usually believed that the electrons run away against the electric field, accelerating. This is how pulsed moving lightning and electric anode-directed arcs are formed with electrons run away (falling out) of them. Observations of such lightning are described in [5], and the theory describing this phenomenon was formulated in [2,4,5]. But, for high-energy electrons, internal electric fields are no longer a decree. Some of them can move in any direction, and even in the direction of the electric field, slowing down slightly. Two opposite streams of electrons are formed. One focuses (cumulates) its energy into the plasma CDS, and the other, having received additional energy, takes the energy out of the plasma CDS. The volumetric charge and electric field of the plasma CDS limits the dissipation of energy from it.

The aim of this work is to simplify the 8D problem we set for taking into account the violation of electroneutrality of plasma CDS and to propose an effective 4D mathematical model describing non-stationary and stationary phenomena in an inhomogeneous plasma with current.

Figure 2: Beaded lightning as a regular cumulative-dissipative system with long-range dynamic order and hyper-properties. L_1 are electron cumulation points theoretically described by Vysikaylo [5].

Figure 3: Plasma cumulative-dissipative structures in air: cylindrical cumulation in linear lightning in Brazil with a characteristic radius of ~ 1.2 m. https://photo.brestcity.com/2023/02/hristos2.jpg

The solution of such a minimum 8D dimensional full-fledged model, which does not even take into account the interaction of dual opposite electron flows with each other in plasma CDS, is currently impossible. However, an explanation of a number of cumulative-dissipative phenomena can be obtained within the framework of inferior models using experimental observations of such plasma CDS. In [11], the electron temperature profile in the entire heliosphere was obtained analytically on the basis of experimentally established varieties of positive iron ions in the heliosphere in [12]. In [11], on the basis of the experimentally established facts in [12] the role of runaway electrons in the effective charge of the CDS–Sun was taken into account and the EMF of the entire heliosphere. Thus, electrons escaping from the Sun and the entire heliosphere are taken into account in the effective charge of the Sun. This allowed the 8D dimensional problem to be reduced to a 4D dimensional problem, and then to a 1D dimensional spherically symmetric quasi-stationary problem. Thus, for the first time in [11], the foundations of a unified plasma heliogeophysics of a quasi-permanent giant discharge between a positively charged Sun and a negatively charged Earth were laid. In [12], despite the general title of the monograph "Plasma Heliogeophysics", heliophysics and geophysics are presented as separate parts that are not connected to each other by a single giant current of charged particles in the heliosphere, which is proved in [11]. In this paper, understanding the complexity of 8D numerical and analytical modeling of specific flows in CDS in plasma, in order to explain a number of "mysterious" phenomena in plasma caused by violation of plasma electrical neutrality, we propose a method for modeling such flows. To do this, we will use our experimental experience in observing the entire spectrum of gas-discharge phenomena in laboratories and reduce the complexity of the 8D problem to 4D or 2D measurements (in space-time), setting the appropriate boundary conditions or CDS electric charge.

Stoletov established that many phenomena in plasma are determined by the electric field strength - *E* reduced to the neutral gas pressure (*P*) – *E/P* [13]. Later, referring to Stoletov, Townsend proved experimentally that for all dependences of the constants of processes (production, excitation, attachment of electrons, drift of charged particles and coefficients of various diffusions) in plasma, it is more efficient to use the parameter of the reduced electric field strength to the density of the number of neutral gas particles – *N*. This is how the parameter – *E/N*, measured in Townsends (1Td = 10^{-17} V•cm^2) appeared in the physics of low-temperature plasma [14]. Breakdown of air occurs when $E/N \approx 90$ Td is reached.

This area continues to develop successfully due to the influence of charged particle transfer processes in the ionosphere and heliosphere on the functioning of systems such as JPS. The importance is the study of the influence of processes in the plasma of the heliosphere and ionosphere on the well-being of man and all organisms of the Earth. However, in astrophysics and physics of the ionosphere the control parameter *E/N* is little used. It believed that a rigorous description of the behavior of not only a weakly ionized gas-discharge plasma, but also the plasma of the heliosphere and ionosphere should be carried out using kinetic equations for electrons and ions [4,9]. This method is very complicated; the approaches developed within its framework with two-particle collisions and a two-term approximation were criticized by A.A. Vlasov and he called them inferior models [3]. This approach is not needed in many cases, and all the questions posed by A.A. Vlasov, are easily removed. Since all transfer coefficients can be taken from experiments, for example, for electron transfer processes from [14,15], for ions from [16] and approximated by simple dependences on the E/N parameter [4]. The system of kinetic equations can be replaced by a simpler system of transfer equations for local macroscopic quantities that determine the behavior of electrons and ions, if three basic conditions are met [4]:

1) Many collisions occur during the characteristic time of the process;

2) The path travelled by the particle between two collisions is much less than the distance over which the macroscopic quantities change significantly;

3) The violation of the electroneutrality of the plasma is small. (In [4], we modified this condition for the first time for a significant violation of the electroneutrality of the plasma with current). These conditions allow us to a perturbation theory for describing shock waves of an electric field [4] in a gas-discharge and in in semiconductors.

Accounting for pair interactions and the formation of electron velocity distribution functions different from the Maxwellian one led to the renormalization of the coefficients of transport processes in an inhomogeneous plasma and the appearance in the theory of a number of transfer processes different from the classical ones [4,9]. In reality, all these "classical" and "neoclassical" processes exist in nature, are observed in experiments (the modification of the effective coefficient of electron diffusion longitudinal to the electric field has been studied in detail) and can be taken into account in modified hydrodynamic models [4,9]. In this case, the coefficients of various diffusions, drifts, reactions (excitation, ionization, recombination, etc.) can be taken from the tables compiled by Townsend and his followers, according to experimental observations [4,14-16]. In this case, the hydrodynamic description will be the most complete and corresponding to already observed and well-studied natural phenomena. All the remarks of A.A. Vlasov to the theory of pair collisions and artificial (not sufficiently substantiated) cutoff of divergent integrals and effective collision cross sections become unjustified. The experimentally measured coefficients take into account all types of collisions (triple, quadruple, etc.), as well as all possible real impact distances (or effective reaction cross sections). These coefficients established in experiments can be used in electrohydrodynamic models, and based on the analysis of these models, new discoveries can be made and refute pseudoscientific conjectures and 1D models that are not related to real phenomena in plasma. Consequently, the application of the kinetic description does not at all mean an expansion of the scope of the equations of hydrodynamics, and perhaps even, on the contrary, narrows them, since it requires the application of a completely specific procedure for solving the kinetic equation, which significantly limits the scope of application of the entire bulky model. Therefore, a simple system of electro-hydrodynamic equations, rigidly based on previously experimentally measured transfer and reactions coefficients, can be formulated in a more general case (in a wider framework) than a system with kinetic equations for plasma components, with a pre-formulated procedure for solving the kinetic equation (with the selected cutoff procedure, the selected consideration of only paired collisions, etc.).

The change in internal long-range electric fields in plasma can be taken into account by supplementing the system of hydrodynamic equations with the Poisson equation. In this case, the system of charged particles becomes not just a multicomponent gas, but some peculiar system, pulled together by distant Coulomb forces (or synergistic electric fields capable of self-organization and formation of cumulative jets from charged plasma particles from cumulative-dissipative structures [3]). We will focus on the analysis and methods for solving specific problems using such a simple and fairly general model, based on experimental data on the processes of transport and ionization of plasma particles, in this work.

Three types of shock waves are currently known [4,17]:
1) Shock waves (or sharp jumps in parameters) in gas dynamics. Their study began with the work of Mach (1881) - Austrian physicist, born in Czechoslovakia;
2) Magnetic field shock waves were described by R.Z. Sagdeev in 1961-1962 in the USSR;
3) Shock waves of the electric field, described theoretically and experimentally in detail in the works of P.I. Vysikaylo in the USSR, see references in [4]. Although, Vysikaylo's shock waves were observed by Faraday, then by Klyarfel'd (1952) in the form of standing and traveling layers in gas-discharge plasma in tubes, and by Gunn (1963) in the form of current oscillations in semiconductors. The cumulation of shock electromagnetic waves was of theoretical interest to E.I. Zababakhin (1957; 1965; 1988). However, the main results on experimental and theoretical research and proof of the existence of electric field shock waves were obtained in the works of P.I. Vysikaylo and his co-authors for almost 40 years, see references in [4,17-20].

The remaining types of shock waves (plasma parameter jumps – pressure of ions, electrons, etc.) can be reduced to these three main types [17] or the Fisher - Kolmogorov - Turing – Prigogine's problem, where diffusion and production (birth, ionization, etc.) or two diffusions with different characteristic diffusion sizes are used, for example, in the case of the Prigogine's Brusselator [21]. From the point of view of describe the concentration profile in the ambipolar drift approximation - terms with the first derivative in coordinates ($V\nabla n$). As $V \rightarrow 0$ this description becomes multivalued (theoretically). In order to obtain physically significant solutions, it is necessary to theoretically take into account smoothing diffusion flows [4,17-20]. This leads to the need to describe a shock wave or a jump in plasma parameters using terms with a second derivative in coordinates ($\nabla D \nabla n$).

As the fourth type of propagation of ultrafast (with velocities exceeding the speed of detonation waves > 10 km/s) disturbances, one can cite the phenomena of co-organization of opposite rotating flows of charged particles or the processes of generation of Vysikaylo's structural turbulence (analogues of tropical cyclones – by-cyclones) [https://aas242-aas.ipostersessions.com/default.aspx?s=A2-09-05-57-8A-37-5A-F3-92-45-FB-FF-F5-17-F5-4F].

In all three cases of shock waves, in order to mathematically describe the profiles of parameters in jumps in plasma or in gas-dynamic flows, researchers have to move from drift profiles described by the first derivatives of coordinates ($V\nabla n$) to diffusion profiles or to terms with the second derivative with respect to spatial coordinates ($\nabla D \nabla n$). Therefore, the description of shock waves (jumps) of all three types is carried out by researchers using similar mathematical methods and equations. This makes it possible to apply the method of generalized mathematical transfer (MGMT) of mathematical models from the fields of natural sciences, where descriptions of similar phenomena are most complete, in the field of sciences, where a similar theoretical study is less complete [22].

In [4,17-19], we constructed a perturbation theory to describe self-forming 4D structures in inhomogeneous plasma with current. 4D plasma structures are non-stationary three-dimensional structures. Referring to Stoletov, Townsend proved experimentally that for all dependences of the constants of processes (production, excitation, attachment of electrons, drift of charged particles and coefficients of various diffusions) in plasma, it is more efficient to use the parameter of the reduced electric field strength to the density of the number of neutral gas particles – N. This is how the parameter – E/N, measured in Townsends (1Td = 10^{-17} V•cm^2) appeared in the physics of low-temperature plasma. Breakdown of air occurs when $E/N \approx 100$ Td is reached. All transfer coefficients can be taken from experiments and approximated by simple dependences on the E/N parameter, see [4,17-19]. In our theory [4,17-19], the main small parameters were the smallness of the electron energy relaxation length – l_u with characteristic dimensions in the problem – L ($l_u / L \ll 1$) and the smallness of the ion current compared to the electron current ($(\mu_i/\mu_e)\boldsymbol{l}_{E0}/L \ll 1$; $\boldsymbol{l}_{E0} = E_0/(4\pi e n_e)$).

2. Transport Equations with Electrical Neutrality Violation

The model of the processes of transport of charged plasma particles without a magnetic field includes the equations for the balance of the number of ions:

$$\partial n_\alpha/\partial t + \mathrm{div}(n_\alpha \boldsymbol{V}_\alpha) = I_\alpha - R\alpha, \qquad (1)$$

where n_α is the concentration of positive or negative ions; $V_\alpha = \mu_\alpha E$ is the ion drift velocity, which is a function of the control parameter E/N. I_α ; R_α - sources and sinks of ions. To equation (1) it is necessary to add electrodynamic equations:

$$\mathrm{rot}\, \boldsymbol{E} = 0; \qquad (2)$$

$$\mathrm{div}\, \boldsymbol{E} = 4\pi\rho, \qquad (3)$$

where $\rho = e\left(\sum_{\alpha=1}^{m} z_a n_a - n_e\right)$; z_α is the ion charge, m is the number of different types of ions. Instead of the electron balance equation (as in the case of ions), we will take into account the total current density. To do this, we add the balance equations for electrons and all kinds of ions (multiplying them by the corresponding charge) and take into account that charged particles of different signs in the volume are born and die simultaneously, using (3), we get:

$$\nabla \boldsymbol{j} = 0, \qquad (4)$$

where $\boldsymbol{j} / e = (\partial E/\partial \mathrm{t})/(4\pi e) - n_e V_e + \sum_{\alpha=1}^{m} z_a n_a \quad V_\alpha + \nabla(D_e n_e)\ldots$
De is the electron diffusion coefficient (… this is an allowance for ion diffusion).

Since electrons and ions in the plasma are born and die together, in the current continuity equation, the sources and sinks are mutually compensated (as are the fluxes due to the non-stationarity and inhomogeneity of the plasma concentration and electric field strength, as well as the non-stationarity and inhomogeneity of the electron velocity distribution function in the sources and stocks). Therefore, the continuity equation for the total current density has the from (4), where $\boldsymbol{j}$ is the total current, taking into account the displacement current – $(\partial E/\partial \mathrm{t})/(4\pi)$ [4,17]. Equation (4) can be modified taking into account (3). From (3):
$n_i = n_e + \nabla \boldsymbol{E}/(4\pi e) \sum_{\alpha=1}^{m-1} z_a n_a$, we will substitute it in (4). In this case, (4) will take the form [4,17]:

$$\boldsymbol{j}/e = 1/(4\pi e)\ (\partial \boldsymbol{E}/\partial \mathrm{t}) - n_\mathrm{e} \boldsymbol{V}_\mathrm{e} + (\sum_{\alpha=1}^{m-1} z_a n_a \boldsymbol{V}_\alpha + z_\mathrm{i} \boldsymbol{V}_\mathrm{i}\ (n_\mathrm{e} + \nabla \boldsymbol{E}/(4\pi e) - \sum_{\alpha=1}^{m-1} z_a n_a\ ) + \nabla(D_\mathrm{e} n_\mathrm{e})\ldots, \qquad (5)$$

where the 5th term with $z_i V_i \ \nabla E/(4\pi e)$ takes into account the influence of the violation of the electrical neutrality of the plasma on the modification of the internal electric field – E [4,17].

3. Perturbation Theory Parameters

The order of magnitude of terms in (5) with respect to the term with a drift structure is determined by the following values: τ_M/τ, 1, $(\mu_\mathrm{i}/\mu_\mathrm{J}) l_\mathrm{E}/L$, l_u/L ... Usually, one can neglect the diffusion of ions, which we will do. Here τ characteristic charge change time, $\tau_\mathrm{M} = 1/(4\pi e \mu_\mathrm{J} n_e)$ Maxwellian space charge neutralization time, μ_J – effective plasma mobility taking into account the mobility of ions and electrons, $l_\mathrm{E0} = E_0/\ (4\pi e n_e)$ vectorized characteristic size of electric field strength change. If the parameters $\Omega\tau_\mathrm{M}$, $(\mu_\mathrm{i}/\mu_\mathrm{J}) l_\mathrm{E}/L$ and l_u/L are small, then the system of hydrodynamic equations and the Poisson equation can be solved using perturbation theory [4,17]. The smallness of the parameter $(\mu_\mathrm{i}/\mu_\mathrm{J}) l_\mathrm{E}/L << 1$ can also be observed at $l_\mathrm{E0}/L >> 10$, since $\mu_\mathrm{i}/\mu_\mathrm{J} \approx \mu_\mathrm{i}/\mu_\mathrm{e}$. Within the framework of our perturbation theory, it is possible to advance in the zero order into the region with a significant violation of electro-neutrality [4,17]. For example, from a positive column, it is possible, discarding the problem of boundary conditions to advance using numerical and analytical calculations into the near-electrode regions. This method is applicable at elevated gas pressures and significant interelectrode gaps and away from near-electrode regions. The null approximation branches into the approximation:
1) Drift or quasi-neutral, when $l_\mathrm{E0}/L << 1$ (see [4,17]) and
2) Vysikaylo-Poisson', when $l_\mathrm{E0}/L \sim 1$ (or even $l_\mathrm{E0}/L >> 10$, but $(\mu_\mathrm{i}/\mu_\mathrm{J}) l_\mathrm{E}/L << 1$ (the main current is carried by electrons $\mu_\mathrm{J} \approx \mu_\mathrm{e} >> \mu_\mathrm{i}$ – ion mobility).

4. The Zero Approximation of our Perturbation Theory

In the zeroth approximation of our perturbation theory, the drift velocity of electrons and ions is described by the relations: $V_\mathrm{e0} = \mu_\mathrm{e0} E_0$, $V_\mathrm{i0} = \mu_\mathrm{i0} E_0$, here are the mobility of electrons – μ_e0 and ions – μ_i0, respectively. From (1), (3) and (5) in the zero approximation ($\mu_\mathrm{J0}\, n_e \nabla E_0 = - E_0 \nabla(\mu_\mathrm{J0}\, n_e)$), we obtain for simple plasma:

$$\partial n_\mathrm{e}/\partial t - \partial[(\boldsymbol{l}_\mathrm{E0}/\mu_\mathrm{J0})\nabla](\mu_\mathrm{J0}\, n_\mathrm{e})/\partial t + (\boldsymbol{j}/\mathrm{e})\nabla(\mu\mathrm{i}_0/\mu_\mathrm{J0}) - \nabla\{(\mu_\mathrm{i0} \boldsymbol{E}_0/\mu_\mathrm{J0})(\boldsymbol{l}_\mathrm{E0}\cdot\nabla)(\mu_\mathrm{J0}\, n_\mathrm{e})\} = \mathrm{I}_\mathrm{i0} - \mathrm{R}_\mathrm{i0}, \qquad (6)$$

4D Vysikaylo' equation (6) is derived from (1) by modifying the ion concentration n_i by n_e-$(l_\mathrm{E0}\ \nabla)(n_\mathrm{e}\ \mu_\mathrm{J0})/\mu_\mathrm{J0}$. The terms with le0 in (6) arises due to taking into account the violation of electroneutrality. The second term with mixed derivatives with respect to time and spatial coordinates has no analogues in hydrodynamics, and the fourth term is analogous to diffusion. In hydrodynamics, the transition from convective to diffusion transfer is observed during the formation of shock waves discovered by Mach. The presence in (6) of a term due to the violation of electrical neutrality allows us to assert that the presence of electric field shock waves in the plasma should be expected. Shock waves of the electric field in gas-discharge were discovered and visualized by Vysikaylo and co-authors in 1985-1987 [4,17]. The presence of 2 and 4 terms in (6) with a mixed derivative will allow us to describe stationary and traveling shock waves of the electric field - strata (parameter E/N) both in ordinary gas-discharge plasma and in the ionosphere and heliosphere, where global currents flow [4,11].

5. Ambipolar Drifts in Current Plasma

The action of various external forces on the charged components of the plasma leads to ambipolar drift of the plasma and its CDS as a whole [4,18].

5.1. Ambipolar Plasma Drift due to different dependences of the Electron and Ion Mobilities on the Electric Field (E/N)

The third term in (6) - $(\boldsymbol{j}/\mathrm{e})\ \nabla(\mu_{+0}/\mu_\mathrm{J0})$ in the zeroth approximation of the Vysikaylo's perturbation theory determines the magnitude of the ambipolar drift of an inhomogeneous plasma due to the different dependences of the electron and positive ion mobilities even in a simple plasma. In an inhomogeneous electric field, the plasma is polarized and, from this polarization, the plasma perturbation acquires an ambipolar velocity and as a whole move towards the anode or cathode (in the one - dimensional case; or towards the to the center of the discharge or to its boundary - the wall in the 3D dimensional case), depending on the ratio and signs of the logarithmic derivatives of the electron and ion mobilities from the electric field - E_0 (or E_0/N). The ambipolar plasma mobility is $\mu_\mathrm{a} = \mu_+(\mu_+^* - \mu_\mathrm{e}^*)/(1+\mu_\mathrm{e}^*)$ [17]. Here $\mu^* = \ln\mu/\ln(E_0/N)$. This implies the expression for the ambipolar plasma drift: $V_\mathrm{a} = \mu_\mathrm{a} E_0$ and (6) takes the form in the 4D drift approximation:

$$\partial n/\partial t + \boldsymbol{V}_\mathrm{a} \nabla n = I_{+0} - R_{+0} \qquad (7)$$

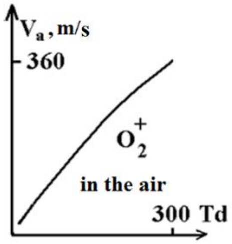

Figure 4: Ambipolar drift velocity – V_a due to different dependences of the electron and O_2+ ion mobilities on the parameter $\gamma = E/N$ [4,17]

The analytically calculated value of the ambipolar drift velocity in air and its dependence on the *E/N* parameter are shown in Fig.4 [4]. In gas discharges, the electron mobility usually decreases with increasing parameter *E/N*, while the mobility of positive ions is almost constant. In this case, the ambipolar drift is directed from small *E/N* values to large ones. For a gas-discharge plasma, this drift in the Faraday dark space is directed from the cathode to the anode [4,17].

5.2. Ambipolar Drift Due to Motion of Neutral Gas

The simplest and longest-studied method for ejecting excited neutral plasma from the discharge gap is pumping neutral gas through the discharge gap. In lasers, to remove already spent products of plasma excitation, longitudinal or transverse gas moving is used at a speed less than sonic [4,22] or even supersonic [23]. Since the positive ions are entrained by the neutral gas (the ions are frozen into the neutral gas), the effective ambipolar plasma drift velocity changes by the value of the gas velocity - *U*, i.e. in (7) the term $U\nabla n$ should be added and (7) will take the 4D form:

$$\partial n/\partial t + (\boldsymbol{V}_a + \boldsymbol{U})\nabla n = I_{i0} - R_{i0} \quad (8)$$

In the case of gas flow transverse to the discharge current, the value of the plasma displacement in the presence of an ambipolar drift due to the difference in the dependences of the mobilities on the field can be estimated from:

$$L_{UG} \sim L_0 U/V_a \quad (9)$$

Here L_0 is the characteristic size of the plasma inhomogeneity, for example, the size of the Faraday dark space. At large *U* and small V_a, there is no exchange of signals by ambipolar drift due to different dependences of the electron and ion mobilities on the field between the parts of the discharge. In this case, the plasma is carried away by a neutral gas flow and striations can appear or new 4D ambipolar drifts are generated, which determine the structure of the new plasmoid and link the parts of the new plasma structure (plasmoid) into a single whole. Similarly, it is possible to estimate the magnitude of the plasma displacement for any other transverse ambipolar drift caused by: a transverse magnetic field, acceleration, or other transverse current effects on certain plasma components, see Sections 5.1–5.7, 5.9.

5.3. Law of Additivity of Ambipolar Drifts

We, see references in [4], have experimentally verified the law of additivity of ambipolar drifts due to longitudinal gas flow and internal ambipolar drift due to different dependences of the electron and positive ion mobilities on the *E/N* parameter in the discharge in high-purity nitrogen with pumping of gas from the cathode to the anode and from the anode to the cathode (Fig. 2). Thus, in [4], we analytically and experimentally proved that the ambipolar drift has additive properties. It follows from (8) that the Faraday dark space shrinks with decreasing U_G and should disappear at $U = -V_a$, the value of the drift in the positive column. Fig.5, dependence 7+, shows the distribution *E/N*(*x*) obtained in the experiment at $U = -164$ m/s ($-U > V_a$).

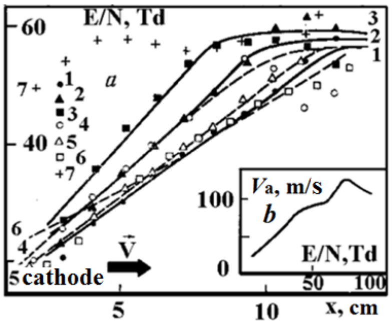

Figure 5: Distribution in the interelectrode gap of the electric field strength related to the concentration of gas molecules - *N*: a) at *P* = 20 Torr (calculation curves, dots - experiment): 1 — j = 4 mA / cm^2, U_G = 73 m/s; 2 — 6, 73; 3 — 10, 73; 4 — 20, 30; 5 — 20, 73; 6 — 20, 164; 7 —20, -164; b) is the rate of ambipolar plasma transfer $V_a = \mu_a E_0$ in nitrogen, calculated under the assumption that the main ion is N_4^+ with constant mobility [4,18].

It can be seen that in this case, too, between the cathode and the positive column with a constant value of $E/N \approx 60$ Td, there is a transition section ~2 cm long, the presence of which is not explained within the considered drift model (3). Such profiles can provide cumulative jets formed in the region near the cathode. Such structured drift ambipolar flows in experiments are associated with the inhomogeneity and non-stationarity of the electron velocity distribution function in ionization processes and can disappear when ionization-recombination equilibrium is established (see Chapters 2 and 4 in [4]). These ambipolar flows arise in the first approximation according to the Vysikaylo's perturbation theory and will be considered by us in the following parts.

The comparisons of various experimental studies and numerical calculations given in [4] (Fig.5) showed that the information available in the literature on the rate constants of elementary processes in nitrogen plasma makes it possible to calculate with good accuracy numerically and analytically the distribution of the electric field strength over the discharge gap in an electrically neutral plasma inhomogeneous self-sustained discharge in a nitrogen flow using equation (8) (i.e., within the framework of the drift approximation).

5.4. Ambipolar Drift and Polarization of Plasma Due to Violation of its Electroneutrality

With a weak violation of the electroneutrality of the plasma, already in the zeroth approximation of the Vysikaylo's perturbation theory [4,17,18], the processes of drift ambipolar transfer of the plasma concentration profiles appear – the second and third terms in (6). The second term in (6) is nonzero in the case of non-stationary profile l_{E0}/μ_{J0}. The non-stationarity of this term is mainly determined by the non-stationarity of the electric field - E_0 (or parameter E_0/N). In this case, the velocity of the ambipolar drift of the plasma concentration profile – n is equal to $V_E \sim \partial \boldsymbol{l}_{E0}/\partial t = \partial(E_0/(4\pi e n_e))/\partial t$ [4,17].

As shown in [4,17], taking into account the mixed derivative (the second term in (6)) allows us to explain the effect observed by L. Pekarik in a gas discharge [24]. This effect consisted in the fact that the group velocity of the striations (as proved in [4], shock waves of the electric field) in Pekarik's experiments described in [24] was opposite to their phase velocity. For the manifestation of such an anomalous dispersion, as indicated by P.S. Landa in [25], in the general case, it is necessary to take into account the mixed derivative with respect to space and time. In [4], the author first showed that such a term with a mixed derivative (with respect to $\partial/\partial t$ and $\partial/\partial x$) in the perturbation theory constructed by Vysikaylo appears when we take into account the violation of electrical neutrality and the nonstationarity of transport processes in plasma [4,18]. So, in (6) the second term appears $-\partial[(\boldsymbol{l}_{E0}/\mu_{J0})\,\nabla\,](\mu_{J0}\, n_e)/\partial t$. Taking this type of ambipolar drift into account, we explained the Pekarik' effect, see [4] for more details.

5.5. Inertial Ambipolar Drift

If the discharge plasma, together with the gas and electrodes, moves with acceleration, then additional forces act on the ions and electrons (in the coordinate system associated with the electrodes) - inertial forces equal to $m{+}\boldsymbol{a}$ and m_{ea}, where $m_{+,e}$ - the mass of the ion and electron, respectively, $\boldsymbol{a}$ - acceleration vector (electron inertia force can be neglected because $m_+ >> m_e$). When such a force acting on ions is taken into account, equation (6) in the drift approximation takes the 4D form [4]:

$$\partial n/\partial t + (\boldsymbol{V}_a + \boldsymbol{U}_{In})\nabla n = I_{i0} - R_{i0}, \quad \boldsymbol{U}_{In} = \mu_+^{1} m_+ \boldsymbol{a}/e \tag{10}$$

Here μ_+^1 - the mobility of ions in the direction of acceleration $\boldsymbol{a}$, arising under the action of the force $m{+}\boldsymbol{a}$. For real accelerations (~ 10 m/s^2), as estimates show, the ion mobility can be considered an isotropic value and equal to μ_+ = const. Where does the velocity of the inertial ambipolar plasma drift come from in this approximation ?:

$$\boldsymbol{U}_{In} = \mu_+\, m_i \boldsymbol{a}/e \tag{11}$$

5.6. Ambipolar Drift and Plasma Polarization in a Gravitational Field

Gravity forces act on positive ions m_+/m_e times stronger than on electrons. The gravitational forces in a collisional plasma can be taken into account, as in the case of an inertial ambipolar drift. In this case, instead of acceleration - and in (10) and (11) one should substitute the gravitational force acting on the ions:

$$\partial n/\partial t + (\boldsymbol{V}_a + \boldsymbol{U}_g)\nabla n = I_{+0} - R_{+0}, \quad \boldsymbol{U}_g = \mu_+ m_+ \boldsymbol{g}/e \tag{12}$$

$\boldsymbol{g}$ is the acceleration due to gravity acting on positive ions.

A. Pannekoek (1922) thought about taking into account the difference in gravitational forces acting on ions and electrons in the solar plasma [26]. More details on the problem of violation of the electrical neutrality of the Sun (with a charge of 1400 C), the entire heliosphere and the generation of global eddy currents in the heliosphere can be found in [11]. The presence of global currents in the heliosphere and violation of its electrical neutrality explains many phenomena of cumulative-dissipative structures in the ionosphere and heliosphere [11].

5.7. Gyroscopic Ambipolar Drift

To describe the gyroscopic effects in the discharge (see references in [4]), we can use a similar approach as in Section 5.5. In this case, taking into account the Coriolis force acting on ions will lead to the replacement in (10) of U_{In} by $U_\omega = 2m{+}[\boldsymbol{E}x\boldsymbol{\omega}]\mu_+/e$, where $\boldsymbol{\omega}$ is the vector of the angular velocity of rotation (for example, capsules with a discharge). The magnitude of the plasma displacement due to the gyroscopic effect in the presence of an ambipolar drift due to the difference in the dependences of the mobilities on the field can be estimated from:

$$L_{U\omega} \sim L_0 U_\omega/V_a = 2L_0(1 + \mu_e^*)m_+\, \mu_+\omega/(e\mu_e^*) \tag{13}$$

According to (13), the displacement - $L_{U\omega}$ depends on the logarithmic derivative of the electron mobility on the field. At large U_ω and small V_a, the exchange of signals by ambipolar drift due to different dependences of the electron and ion mobilities on the field does not occur between the parts of the discharge. The discharge stops, plasmoids die or new transfer processes are generated, generating new plasma nonlocal inhomogeneous and non-stationary structures [4].

5.8. Plasma-Chemical Ambipolar Drift in Electronegative Gases

In electronegative gases, free electrons quickly attach to molecules (with a high affinity for free electrons) of electronegative gases. In this case, the system of equations for the transfer of charged particles (electrons, positive and negative ions) can be solved in the adiabatic approximation [4], i.e. instead of the transport equation for negative ions, use the point equation $I_{-0} = R_{-0}$. Let us confine ourselves to the assumptions: j = const, $I_{-0} = \nu_{a0} n$, and $R_- = \nu_d\, n_-$, where ν_{a0} is the frequency of formation of negative ions, which is a function of the parameter $\gamma = E_0/N$, νd is the frequency of destruction of negative ions (let ν_d = const). According to the above, the concentration of negative ions is $n_- = n\nu_{a0}/\nu_d$, and in the approximation of a small current of positive ions compared to the current of electrons, we obtain from the transfer equation for positive ions in the drift zeroth approximation the following equation for the electron concentration [4]:

$$A(n)\partial n/\partial \mathrm{t} + V(n)\partial n/\partial x = I_{+0} - R_{+0} \quad (14)$$

где $A(n) = 1+\nu_{a0}\,(1 - \nu^*_{a0}/(1 + \mu^*_{e0}))/\nu_{d0}$, $\boldsymbol{V}(n) = \boldsymbol{V}_{a0} + \boldsymbol{V}_{c0}$, $\boldsymbol{V}_{a0} = -\mu_+ E_0\,(\mu^*_e + \mu^*_+)/(1 + \mu^*_e)$, $\boldsymbol{V}_{c0} = -\mu_+ \boldsymbol{E}_0\,(\mu^*_e - \mu^*_+ - \nu^*_{a0})\,\nu_a/[\nu_d\,(1 + \mu^*_e)]$, $\nu^*_{a0} = \partial \ln \nu^*_{a0}/\partial \ln \gamma$.

Since V_{c0} is determined by the frequencies of plasma chemical reactions (ν_{a0}, ν_d), this component of the ambipolar drift can be called the plasma-chemical ambipolar drift [4]. For stationary and quasi-stationary profiles, the characteristic size of in-homogeneities L is determined by the velocity $V(n) = V_{a0}+V_{c0}$ [$L \sim nV(n)/(I_{+0} - R_{+0})$]. The distribution of concentration and field profiles or their establishment, according to (13), is determined not only by the velocity $V(n)$, but also by the coefficient $A(n)$. Wave profile point velocity $V_p = V(n)/A(n)$ [4].

The presence in electronegative gases, for example, in air, of an ambipolar drift, which is more powerful than in electropositive gases, due to plasma-chemical processes, can lead to inhomogeneous parameter profiles, and, consequently, to more powerful and sharp cumulative processes that form cumulative plasma jets. These phenomena are realized in the upper atmosphere in the form of sprites, jets, elves, and other cumulative-dissipative structures.

5.9. Ambipolar Drift in a Magnetic Field

We have considered above the cases when external forces acted on the ions and did not have a noticeable effect on the electrons. In a discharge in a magnetic field, the Lorentz force acting on more mobile electrons significantly exceeds the analogous force acting on positive ions (by a factor of μ_+/μ_e). Let us restrict ourselves to considering a weak ($\mu_e H/c \ll 1$) stationary external magnetic field with strength – $\boldsymbol{H}$ directed perpendicular to the electric field strength – $\boldsymbol{E}_0$. In this case, instead of (7) we obtain the 4D equation for an ambipolar plasma flow in a magnetic field with pumping gas in form [4]:

$$\partial n/\partial t + (\boldsymbol{V}_a + \boldsymbol{U} - \mu_+\mu_e[\boldsymbol{E}\mathbf{x}\boldsymbol{H}]/\mathrm{c})\nabla n = I_{+0} - R_{+0} \quad (15)$$

The effect of gas pumping on the plasma transport as a whole (in the direction perpendicular to both the electric and magnetic fields) can be compensated by applying a magnetic field with the value $\mathrm{H} = \mathrm{c}U/(\mu_i\,\mu_e \mathrm{E})$, where c is the speed of light.

5.10. Application of Magnetic Fields to Study Plasma with Current

The first measurements of the Earth's magnetic field using a compass were made in Italy in 1436 [27]. This happened long before Newton's 1686 investigations of gravitational forces and Coulomb's investigations of electric forces in 1785. Therefore, the magnetic paradigm arose before the sciences of gravity and electricity appeared, although plasma (fire and lightning) and light, and hence electric fields, have always accompanied man. For this reason, for researchers who do not take into account the violation of the electrical neutrality of the plasma and the finiteness of all characteristic sizes of inhomogeneous charged structures in plasma, many phenomena in magnetic fields will be paradoxical. For example, J. Stark in 1903 and followed by Weintraub in 1904, followed by a huge number of researchers, discovered the reverse movement of the cathode spot in a magnetic field.

Stark' experiments clearly showed that some of the electrons in the region of the cathode spot move in the wrong direction, i.e. – to the negative cathode (fig.1.)! This means that the cathode spot is an attractor for these electrons and, therefore, is positively charged! But, if we assume that all electrons return to a positively charged structure, then the question arises, how does the electron current flowing from the cathode spot to the anode occur? From these classical Stark' experiments it unambiguously follows that in the region of the cathode spot, electrons are discriminated in space in the region of the cumulation point in terms of their energy. High-energy electrons leave the cathode spot region through cumulation points (foci) [5,17], while low-energy electrons return to it by the synergistic field of positive ions, which form the cathode spot as a whole. Consequently, depending on the energy, the synergistic electric field of the cathode spot (positively charged structure) splits (discriminates, selects, etc.) the electrons into two "peoples" functioning differently in space. Weakly energetic electrons determine the local charged structure (its dimensions and properties), while high-energy electrons carry out the connection between global positively charged structures. (I wonder what experiments with striations in a transverse magnetic field will show).

6. Electric Field Shock Waves and Plasma Nozzles in Inhomogeneous Plasma with Current

For the study of Vysikaylo's shock waves of the electric field and self-organizing Vysikaylo's plasma nozzles in inhomogeneous plasma with current we sing the Vysikaylo's perturbation theory in the zero (6) and first approximation (8) [4,17-19]. 4D equation (16) was obtained that describes the ambipolar transfer of parameters of a simple plasma (with electrons and one type of positive ions) with current. In this equation, terms with the first derivatives of the electron concentration (or electric field) with respect to coordinates, in the zero approximation, describe ambipolar drifts of various natures [4,17-19], and in the first approximation according to the Vysikaylo's perturbation theory, terms with the second derivatives describe ambipolar diffusions and ambipolar drifts due to the inhomogeneity of sources and sinks of charged plasma particles ($E = E_0+E_1$) [4,19]. Vysikaylo's perturbation theory is the most complete modification of Schottky's perturbation theory, which described the processes of ambipolar diffusion. In contrast to Schottky's theory, we took into account all ambipolar drifts caused by the influence of electric field inhomogeneity ($E_1 \sim (D_e/\mu_e)\nabla n_e$ – due to electron diffusion processes [4, 17-19]) on the processes of birth and death of charged plasma particles.

From the Poisson's equation (3) for the electric field (in simple plasma with one type of positive ions - n_+) we get $n_+ = n_e + \nabla E/(4\pi e)$ and from (5) $\nabla j = 0$ it follows $\mu_{e0}\, n_e \nabla E_0 = - E_0 \nabla (\mu_{e0}\, n_e)$. If the death of the plasma is determined by the processes of the recombination of positive ions with electrons $R_i = \beta n_e n_+$, then we can take into account the recombination flows in an inhomogeneous plasma (with a current):

$$R_i = \beta n_e n_e + \beta n_e \nabla \boldsymbol{E}/(4\pi e) = \beta n_e^2 - \beta n_e(\boldsymbol{E_0}/(4\pi e \mu_{e0}\, n_e)\nabla(\mu_{e0}\, n_e)) = R_{i0} - \beta n_e(\boldsymbol{l}_{E0}/\mu_{e0}))\nabla(\mu_{e0}\, n_e).$$

The 4D equation of the balance of positive ions is modified taking into account the violation of electro-neutrality [4,17-19]:

$$\partial n_e/\partial t - \partial[(\boldsymbol{l}_{E0}/\mu_{e0})\nabla](\mu_{e0}\, n_e)/\partial t + (\boldsymbol{j}/e)\nabla(\mu_{+0}/\mu_{e0}) + \boldsymbol{U}\nabla n_e - \nabla(\boldsymbol{U}(\boldsymbol{l}_{E0}/\mu_{e0})\nabla(\mu_{e0} n_e)) - \nabla\{\boldsymbol{l}_{E0}(\mu_{+0}\boldsymbol{E}_0/\mu_{e0}\nabla)(\mu_{e0} n_e)\} - \beta n_e(\boldsymbol{l}_{E0}/\mu_{e0})\nabla(\mu_{e0}\, n_e) = I_i - R_{i0};\ \boldsymbol{l}_{E0} = \boldsymbol{E}_0/(4\pi e n_e) \qquad (16)$$

Here the terms with the ***vector*** – $\boldsymbol{l}_{E0}$ appeared from the Poisson equation for the electric field strength (E) $n_+ = \nabla \boldsymbol{E}/4\pi e + n_e$ and the conditions for the current density $\nabla \boldsymbol{j} = \Omega(e\mu_e E n_e) = 0$; $\beta n_e \boldsymbol{l}_{E0}$ is the speed of the ambipolar recombination flow caused by the violation of electrical neutrality in the plasma with current [4,19], U is the gas pumping speed, β is the effective coefficient of ion-electron recombination. $\boldsymbol{l}_{E0}$ – vectorized characteristic size of the electric field strength inhomogeneity [4] determines the dimensions (including in orthogonal directions due to space charge) of the transition regions of stationary and non-stationary inhomogeneous plasma 3D structures. The second term with mixed derivatives with respect to time and spatial coordinates has no analogues in hydrodynamics (this term describes the Pekarik‘s effect [4, 17-19]) and the sixth term (in the 1D approximation) is similar to diffusion. However, due to the vectorization of the Vysikaylo-Poisson‘s ambipolar diffusion coefficient, charged 3D plasmoids have a number of geometric features, different from Mach‘s shock waves. For example, longitudinal and transverse diffusion processes and the corresponding characteristic transition profiles (3D dimensions) are significantly determined by the local component of the electric field and the concentration of electrons (and not ions!) [4,17-19]. For limited three-dimensional plasma structures, 3D features also appear in this fourth term, leading, in particular, to additional ambipolar diffusion removal of gas-discharge plasma to the walls of the gas-discharge tube (see [18]) in the direction orthogonal to the discharge current. This leads to a local increase in plasma loss on the tube walls, a local increase in the *E/N* parameter, and a local increase in the glow intensity in the shock wave of the electric field. The third term in (1) describes the ambipolar drift of the plasma, caused by different dependences of the electron and ion mobilities on the parameter *E/N*. In nitrogen of a special frequency it can reach up to Va ≈ 70 m/s and is directed from small to large values of E/N. In nitrogen, it is directed from the Faraday dark space to the anode [17-19].

The presence of 3D vectors lE0 in transfer coefficients has not yet been studied in sufficient detail. Their presence indicates the possibility of forming processes of ambipolar 3D transfer of plasma profiles and the generation of both sputtering processes and dynamic surface tension of inhomogeneous plasma 3D structures.

In [18] we will focus on detailed a one-dimensional theoretical description of Vysikaylo’s shock waves of electric fields with violation of electrical neutrality, arising in a region of previously homogeneous plasma (with current), locally perturbed by an external ionizer. This makes it possible not to take into account complex effects in the near-electrode regions and to focus on the very effect of the formation of a layer of positive space charge in the local plasma volume (with current).

Due to the nonlinearity of transfer processes in plasma, the ionizer can work like a piston in both directions from the ionization region and along the field and against the electric field [17].

In [17] we will limit ourselves to the zeroth approximation taking into account the violation of plasma electrical neutrality (1) (we will take into account the Poisson equation for the space charge) [4,17-19]. Note that in [20] there is a small text in Chapter 9.5 (with references to my personal work and to experimental works with my co-authors) about 3D transport processes caused by the violation of electrical neutrality in collisional plasma. There are also photographs of inhomogeneous collisional plasma with 3D shock waves of the electric field, which I predicted and were stopped by pumping gas in the opposite direction to the speed of propagation of the shock wave of the electric field. I personally gave these photos to L.D. Tsendin back in 1988 and allowed him to publish them in [20]. In [20] there is a brief and incomplete theoretical analysis performed by me and L.D. Tsendin, local disturbance by a beam of fast electrons of a previously homogeneous plasma of a positive column in a gas-discharge tube far from the electrodes. I came up with such a disturbance scheme far from the electrodes, L.D. Tsendin helped me in its analytical description with the shock wave predicted by me and the 1D plasma nozzle. There is a corresponding reference to our joint work in [20, chapter 9.5, p.p 282-289]. Currently, a number of these works, in Russia, have been lost due to the negligence of the editor-in-chief of Sov. J. Plasma Phys. The reference and the text of the work are given by us in [4, see the reference – [164], the equation 4.4]. In that work in 1985, I was the first (in 1985) to theoretically obtain terms 5 and 7 in (16) and thereby describe: 1) the processes of ambipolar transfer due to the violation of electrical neutrality and 2) the interference of electric fields when gas is pumped through an inhomogeneous plasma with current. The importance of these terms – 5 and 7 in (16) in experiments is discussed by me for the first time in [18].

In theory and experiments, we have proven the property of additivity of ambipolar drift velocities [4, 18]. This law allows you to control the speeds of internal ambipolar drift by such external influences as a magnetic field, pumping neutral gas, external ionizer (UV or beam of high energy electrons, protons) etc. We have proven in [4,18] that shock waves in plasma or drift jumps arise in regions where the effective speeds of ambipolar drift tend to zero, and the transfer processes are determined by certain processes of ambipolar diffusion. In experiments, see references in [4,20], we, using gas pumping, created such conditions in the gas-discharge plasma that in several areas of the discharge the velocities of the effective ambipolar drift became equal to zero and in these areas Vysikaylo's shock waves of the electric field arose or self-formed plasma 3D structures – Vysikaylo's plasma nozzles similar to Laval' nozzles in gas dynamics [4]. Back in 1985, we discussed the possibility of the occurrence of drift jumps in parameters in a gas-discharge plasma (electric field shock waves) far from the electrodes. P.I. Vysikaylo in 1985, see references in [4,20], the existence of shock waves with violation of electrical neutrality was first predicted. Already in [4,18,19], we classified drift jumps into diffusion (previously known), with violation of electrical neutrality, and complex ones, in which the role of the influence of violation of electrical neutrality (Vysikaylo-Poisson's diffusion) and ambipolar Schottky's diffusions or Vysikaylo-Euler's diffusions are comparable (see Fig.3 in [19]). Vysikaylo's shock waves are realized in regions where the speed of effective ambipolar drift at the first coordinate derivative of the electron concentration vanishes ($V_a = 0$) and to take into account ambipolar transfer it is necessary to take into account effective ambipolar diffusion ($\nabla D \nabla n$) [4,17-19].

In this work, we study two types of electric field shock waves (drift shocks) with violation of plasma electrical neutrality. In the first case, a jump is observed inside the region of the external ionizer (the case of a weak disturbance), in the second - in the region outside the ionizer (the case of a strong ionizer). In the theoretical description we will act in accordance with the works [4,17-20]. In the analytical and numerical study of Vysikaylo's shock waves, we will limit ourselves to stationary one-dimensional, flat and spherically symmetric cases. Unlike classical Mach's shock waves, Vysikaylo's shock waves generate transverse (radial) electric fields due to the space charge in these waves, see (16). On base (16), we will discuss the 3D structures and 4D phenomena that arise from this, see also Part 6.2 of this work.

6.1. Theoretical Studies Vysikaylo's Cumulative - Dissipative Structures in Plasma with Current

6.1.1. Vysikaylo's Plasma Nozzles and Shock Waves in the Electropositive Gas. Drift approach

The question of boundary conditions in a gas-discharge plasma is quite complex, but proposed by P.I. Vysikaylo and implemented in experiments, see references in [4,20], the method of local plasma perturbation far from the electrodes allows us to limit ourselves to the situation when in an infinite, homogeneous positive plasma column there is a local source of ionization of gas molecules (for example, an electron beam). This allows us to remove the problem of boundary conditions at the electrodes when modeling experimental observations.

In the one-dimensional, stationary, drift approximation (in the zero and electron-neutral approximation according to Vysikaylo's perturbation theory) according to [17-19] from the equation (16) of transfer of positive ions in a gas-discharge plasma with gas pumping at a speed U and ambipolar drift – V_a due to different dependences of the electron mobilities – μ_e and positive ions – μ_+, the equation follows:

$$d\boldsymbol{\Gamma}_+/dx = (U+V_a(n))\boldsymbol{\nabla} n = I(n, E(n), x) \tag{17}$$

The electric field – $E(n)$ in (17) is related to the electron concentration – n by the condition of maintaining the current density: $j = e\mu_e En$ (the ion speed and gas pumping U are considered small compared to the electron drift speed);

$$V_a(n) = d(\mu_+ En)/dn = \mu_+ E(\mu_e^* - \mu_+^*)/(1+ \mu_e^*) \tag{18}$$

$\mu_{+,e}^* = \partial \ln \mu_{+,e} / \partial \ln E$; $\mu_+ En$ – flow of positive ions in an electric field. Usually it is $|\mu_{+*}| \ll |\mu_e^*|$, $-1<\mu_e^*<0$, so that $V_a(n)$ is directed from small values of the parameter E/N to large ones. Such an increasing (from the cathode to the anode) profile of the E/N parameter appears in the Faraday dark space towards the positive plasma column (towards the anode, see Fig.5). The quantity V_a+U is the speed of propagation of disturbances and drift of plasma concentration and its role is similar to the speed of sound in conventional gas dynamics. If pumping is also carried out to the anode, then according to the law of additivity of ambipolar drifts of various natures [4,19] $V_a + U<0$, for any n and, therefore, plasma disturbances are carried to the anode. In this case, everywhere away from the electrodes there is a smooth drift profile that satisfies equation (17). In experiments we will find conditions when its scale $L \sim n(V_a+U)/I \gg l_u, l_E$ [4,17]. If pumping is carried out to the cathode $U > 0$, then the graph of the flow of positive ions – $\Gamma_+(E) = (\mu_+ E+U)n$ has a minimum (Fig.6) at $E = E_0$. As U increases, the value of E_0 increases. Smooth solutions corresponding to the drift of disturbances to the anode $V_a+U>0$ are possible only if $E > E_0$ everywhere. Ambipolar drift profiles with $E<E_0$ correspond to the ambipolar drift of plasma parameters by pumping gas – U to the cathode. As $E \to E_0$, the total velocity of the ambipolar drift changes sign, and the scale of the drift solution L becomes zero, so solutions in the form of only drift profiles in which E passes through E_0 are not always possible [4,20]. In this case, two options are possible.

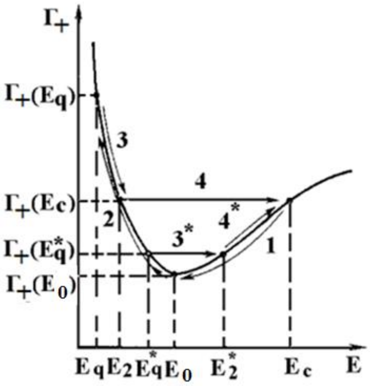

Figure 6: Dependence of the flux of positive ions – $\Gamma_+(E)$ on the electric field – E and the phase portrait of the drift solution of equation (2) for the case of a strong (1-2-3-4) and weak (1-2-3*-4*) beam high-energy electrons disturbing the positive plasma column.

In the first variant, according to (17), drift profiles of plasma parameters are realized, but at $E = E_0$, an inflection point occurs in the electron concentration profile, since:

$$dn/dx|_{x=x0} = I(n_0, E_0(n_0), x_0)/(U+V_a(n_0)) = \infty \tag{19}$$

Let us consider in detail the case U> 0, and let:

$$I = q(x)+\nu_i (E)n - \beta n^2 \tag{20}$$

– a homogeneous column of plasma is acted upon by a local ionization source $q(x)$ – ionization rate [cm^{-3}/s] by a beam of high-energy electrons. Far from the ionizer, the field in the positive plasma column is determined:

$$\nu_i(E_c) = \beta n_c \tag{21}$$

Let $E_c > E_0$, the beam shape is close to Π – shaped ($q(x) \neq 0$ for $x_0 < x < x_1$), and its area of action $l_q = x_1 - x_0$ is long enough so that ionization-recombination equilibrium is achieved in it, corresponding $E_q < E_0$:

$$\nu_i(E_q) \cdot n_q + q(x) = \beta \cdot n_q^2 \tag{22}$$

If $E_q > E_0$, then $E > E_0$ is everywhere and there is a smooth drift profile defined by (2). As one approaches the ionizer from the anode side, the field corresponding to the drift solution decreases and the concentration increases (arrow 1, in Fig.6). The plasma is brought here from the beam area. The concentration profile is determined according to (17):

$$\int ((V_a(n')-U)/(\beta(n')^2 - \nu_i(n')n'))dn' = x - x_0 < 0; \tag{23}$$

in this case $E_c > E > E_0$. See [4,20] for details.

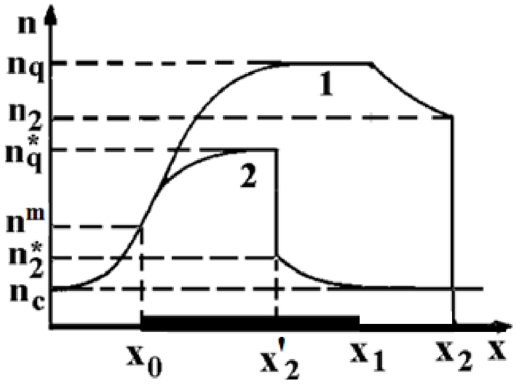

Figure 7: Characteristic plasma concentration profiles for a strong (curve 1) and weak ionizer (curve 2).

In the region of external ionization by a beam of fast electrons, where the field – E is small and, therefore, according to (18), $V_a(n)$ is also small, plasma transfer occurs in the opposite direction (arrow 2, in Fig.6). The concentration and field profile here is determined according to (17):

$$\int ((V_a(n') +U)/(\beta(n')^2 - \nu_i(n')n' - q))dn' = x - x_0 > 0. \tag{24}$$

The plasma concentration in this region gradually increases with x, reaching the equilibrium value nq (22) at a length ~ $(V_a + U)/(q\beta)^{0.5}$ from the point x_0, where $E = E_0$, $n = n_0$. The position of this point is determined according to $I(n, E(n), x_0) = q(x_0) + \nu_i(E_0)n_0 - \beta(n_0)^2 = 0$. In a small vicinity of this point, the concentration profile of plasma particles can be considered linear and can be (19) expand into a series around $x = x_0$ [4]. The sharp boundary of the Π-shaped source corresponds to $dq/dx \to \infty$. In this case, the concentration gradient in this region increases, so that diffusion or violation of electrical neutrality becomes significant [4]. The value $dn/dx|_{x=x0}$ in a real environment therefore remains finite in this case. In the drift approximation, the derivative at the point x0 tends to infinity. This point corresponds to the inflection point in the concentration profile and, accordingly, the electric field.

The gas-dynamic analogue of this point is the critical section in the Laval's nozzle. A drift jump in the concentration and electric field strength in the region x0 is not formed (Fig.7).

Here, to the left of the area of action of the high-energy electron beam, a plasma structure with an inflection point in the electron concentration self-forms. Since the characteristic size of the violation of electrical neutrality is determined by the vectorized size $\boldsymbol{l}_{E0} = E_0/(4\pi e n_e)$ (16) [4], we can assume that an increase in the electron concentration in the region of the inflection point – x_0 will be accompanied by a narrowing of the discharge (from $x = 0$ to $x = x'_2$ or x_1). Such a self-forming 3D nozzle in plasma was opened analytically and then experimentally studied in the works of Vysikaylo and co-authors, see photos in [4,20] and Part 6.2 of this work. We will call this nozzle – the Vysikaylo's plasma nozzle.

In the second variant, in places where $E \to E_0$, $n \to n_0$ in the gas-discharge plasma with gas pumping and current, shock waves or drift jumps are realized (Fig.7), i.e. jumps in drift solutions (Fig.6, curves 3,4 and 3*, 4*) [4,20]. To describe them, one should involve ambipolar diffusion processes [1] or take into account the violation of electrical neutrality [4,17-19]. In drift shocks (shock waves), plasma parameters change sharply on scales ~ max (l_u, l_E) [4,17-20]. To describe profiles in a shock, it is necessary to move on to mathematical models with the second derivative with respect to the coordinate [4]. This is the mathematical justification for the term electric field shock wave, introduced by Gann in 1963 without proper theoretical and experimental justification. Only in the works of P.I. Vysikaylo and his co-authors, shock waves of the electric field have been studied experimentally and theoretically in [4,17-19].

To describe transition profiles in the drift approximation, in this case too, we can use equation (17). The increase in E from E_q to E_c – in the positive plasma column near the right boundary of the beam ($x = x_1$) occurs differently depending on the intensity of the ionizer (high-energy electron beam).

In the case of a strong beam $\Gamma+(E_q) > \Gamma+(E_c)$ up to the point $x = x_1$ the field $E = E_q$. At $x > x_1$ there is a section of the drift solution similar to (23) (arrow 3, in Fig.6). Plasma is brought here from the region $x < x_1$ and recombines. In this case, Γ_+ decreases. This profile continues to point x_2, E_2, where Γ_+ reaches the value of the ion flux in the positive column $\Gamma_+(E_2) = \Gamma_+(n_2) = \Gamma_+(E_c)$. At this point, the field and concentration change abruptly (arrow 4, in Fig.6) to E_c, n_c, determined by equation (21). The concentration profile corresponding to such a jump is shown in Fig.7 by curve 1. The coordinate of the jump x2 is determined by the equation:

$$x_2 = x_1 + \int_{n1}^{n2} \{[V_a(n`) + U]/[\beta(n`)^2 - n`\nu_i(n`)]\}dn`, \tag{25}$$

For a weak beam $\Gamma_+(Eq^*) < \Gamma_+(E_c)$ the jump is realized in the region of action of the ionizer. Plasma from the region $x > x_1$, i.e. from the right side of the column is introduced into the ionizer region with a speed $(V_a(n)+U)<0$ and as it moves towards the anode, its concentration increases according to (16), as it accumulates under a beam of high-energy electrons – $q(x)$.

In this case, the electric field strength decreases from $E = E_c$ at $x = x_1$ to the value E_2^*, which is determined from the condition $\Gamma_+(E_2^*)=\Gamma_+(n_2^*)=\Gamma_+(E_q^*)$, and the plasma concentration increases from n_c to n_2^* (arrow 4*, in Fig.6). Further in the jump, the field drops to E_q^* (arrow 3*, in Fig.6), and the concentration jumps to n_q^*. The coordinate x_2^* of the shock is determined by the drift equation:

$$x_2' = x_1 + \int_{nc}^{n2^*} \{[V_a(n`) + U]/[n`\nu_i(n`) + q - \beta(n`)^2]\}\, dn`, \tag{26}$$

The resulting concentration profile is shown in Fig.7 (curve 2).

Thus, transition sections to stationary jumps in drift solutions, regardless of the structure of the 1D jump, can be described in the drift, electrically neutral approximation. In this case, the transition profiles of drift solutions, in addition to ambipolar drift, are determined by ionization-recombination processes, so the study of plasma profiles in experiments can, in principle, be used to roughly determine the rate constants of these processes. In this case, the 3D geometry of parameter profiles in the Vysikaylo's plasma cumulative-dissipative structures should be taken into account (Fig.6.1 in [4], see also Fig.9.9 in [20], presented by me to L.D. Tsendin). The asymmetry of the 3D structure of the shock and the 3D structure of the Vysikaylo's plasma nozzle in a plasma with current (Fig.7) makes it possible to determine the direction of the electron and, accordingly, ion current. Note that when comparing with experiments, we will pay special attention to recombination ambipolar flows caused by a violation of electrical neutrality $-\beta n_e(\boldsymbol{l}_{E0}/\mu_{e0})\,)\Delta\,(\mu_{e0}\, n_e) \sim -\beta_{E0}\,\Delta n_e$ – the seventh term in (16) and flows caused by the interference of gas pumping with a violation of its electrical neutrality in an inhomogeneous plasma with current $-\Delta(U(\boldsymbol{l}_{E0}/\mu_{e0})\Delta(\mu_{e0}n_e))$ –the fifth term in (16). This ambipolar plasma flows was discussed only in [4]. The first comparisons of theory with experimental observations of these ambipolar flows will be made in Part 6.2 of this work.

6.1.2. Theoretical Description of Profiles in Vysikaylo's Stationary Shock Waves

To describe the structure of a stationary Vysikaylo's shock wave (with a significant violation of electrical neutrality) stopped by gas pumping we first limit ourselves to the case $l_E > l_u$. In this case, the Poisson' equation for the electric field should be added to equation (17) and take into account that the smallness of $\boldsymbol{l}_E$ compared to the scale of the drift solution corresponds to the conservation of $\Gamma_+ = \Gamma_{+0}$ throughout the standing shock wave of the electric field [4,20]:

$$d\Gamma_+/dx = d[(U + \mu_+ E)n_+]/dx = \nu_i(E_q)n_q + q(x) - \beta n_+ n_e \approx 0, \tag{27}$$

$$dE/dx = 4\pi e(n_+ - n_e), \tag{28}$$

in this case $n_e = j/[eE\mu_{e0}(E)]$.

To describe the field profile in a shock, substituting n_+ from the Poisson equation (28) into (27) and integrating (27), we have an equation with separable variables [4]:

$$(U + \mu_+ E)dE/dx = 4\pi e[\Gamma_{+0} - j(\mu_+ E + U)/(e\mu_{e0}E)], \tag{29}$$

The solution, which is in the case of a strong Vysikaylo's shock wave:

$$x = x_2 + \int_{E2}^{E} dE(U+\mu_+ E)/\{4\pi e[\Gamma_{+0} - j(\mu_+ E + U)/(e\mu_e E)]\}, \tag{30}$$

and in the case of a weak jump:

$$x = x_2' + \int_{E2}^{E} dE(U + \mu_+ E)/\{4\pi e[\Gamma_{+0} - j(\mu_+ \mathrm{E} + U)/(e\mu_e E)]\}, \tag{31}$$

The right side of (29) represents the positive difference between the true ion flux and their flux in the drift, neutral approximation (Fig.6). Therefore, the solution corresponding to a jump in which the profile exponentially tends to the neutral approximation at $x \to \pm\infty$ corresponds to $dE/dx > 0$. If $\Gamma+(n)$ has a minimum (Fig.6), then jumps in plasma with current are possible only from small fields to large ones, see references in [4,20]. The gas-dynamic analogue of such shocks is ordinary Mach shock waves. Relations (29) - (31) were obtained in the zero approximation in l_u/L and in the zero approximation in $\mu_+ l_E/L\mu_e$, taking into account the violation of plasma electrical neutrality. Here we obtained parameter profiles in Vysikaylo's shock waves, where the main diffusion process is diffusion caused by a violation of plasma electro-neutrality.

In [4,19], we proved that ambipolar diffusion processes are additivity, like drift ambipolar velocities, and they can be added [4,19]. This means that it is possible to obtain profiles in a shock wave (in a shock wave) even when taking into account the first approximation in l_u/L, i.e. taking into account the ambipolar diffusion of Schottky and Vysikaylo-Euler and Vysikaylo-Poisson in the general case and thus expand the scope of the proposed hydrodynamic approach. To do this, it is necessary to add the effective coefficients of ambipolar diffusion to the coefficient of ambipolar diffusion of charged particles caused by the violation of electrical neutrality. In this case, for stationary diffusion-Poisson's jumps (with mixed profiles) we have [4]: $\Delta x =$

$$\int_{n2}^{n} dn[D_a+(U+\mu_+E)\boldsymbol{l}_E/(1+\mu_e^*)]/[\Gamma_{+0} - j(\mu_+E+U)/(e\mu_{e0}E)]\} \quad (32)$$

where D_a should generally be understood as the sum of the coefficients of all ambipolar diffusions that arise due to taking into account the inhomogeneity of the electron velocity distribution function in the drift velocity of electrons and the processes of birth and death of ions [4]. In this case, undoubtedly, the renormalization of the ambipolar drift should also be taken into account due to the inhomogeneity of the electron velocity distribution function in the processes of ion creation and death (see [4]), but writing such expressions, as is understandable, becomes excessively cumbersome and complex for perception. Therefore, we limit ourselves to representation (32), from which it is clearly seen that under the condition $l_E > l_u$ the jump width is:

$$\boldsymbol{l}_c \sim \boldsymbol{l}_E = \boldsymbol{E}/(4\pi e n_e), \quad (33)$$

which means it decreases with increasing electron concentration, but increases with increasing electric field in the shock. Therefore, with increasing current, the width of the Vysikaylo's shock wave can increase due to a local increase in the *E/N* parameter [4].

Another important conclusion follows from (33) that the width of the jump with a strong ionizer does not depend on the intensity of the ionizer and is determined by the reduced electric intensity to the electron concentration in the positive column, i.e. from one plasma parameter.

6.1.3. Numerical Simulation of Parameter Profiles in 1D Vysikaylo's Shock Waves

Numerical modeling of electric field shock waves stopped by gas pumping was carried out in several ways:

1) By the method of joining integral curves, see references in [4] and

2) Solving a boundary value problem, which was carried out by several methods, see references in [4], including the iterative method [1] and the establishment method [4].

The results of the numerical experiment are shown in Fig.8. Curves 1 and 2 correspond to a weak shock wave (a jump in plasma parameters with a weak external ionizer), and 3 and 4 to a strong Vysikaylo's shock wave (a jump with strong ionization). As shown by numerical experiments, the minimum shock width is realized in the intermediate case between a weak and a strong ionizer (high-energy electron beams).

To the left of the external ionizer (from the region ↑↑↑↓↓↓) in Fig.3 you can see the inflection area in the concentration of charged plasma particles. This region corresponds to the region of self-formation in the plasma cumulative-dissipative structures of the Vysikaylo's nozzle.

In the first case, as the discharge current increases, electro-neutrality is more weakly violated, as a result of which, in numerical calculations, the width of the Vysikaylo's shock wave increases. With a further increase in the discharge current, the ambipolar drift will everywhere be greater than the gas pumping speed, and the concentration profile in the entire plasma column will be described in the drift approximation, i.e. stationary jumps will not be implemented. As the discharge current decreases, one can arrive at the case of a strong beam, i.e. the shock leaves the area of action of the ionizer; in numerical calculations its width increases, as in the experiment, see references in [4].

To the left of the external ionizer (from the region ↑↑↑↓↓↓) in Fig.8 you can see the inflection area in the concentration of charged plasma particles. This region corresponds to the region of self-formation in the plasma cumulative-dissipative structures of the Vysikaylo's nozzle. In numerical calculations we did not take into account the 5th and 7th terms in (16). Therefore, the inflection point in the plasma nozzle is formed strictly at the boundary of the action of the high-energy electron beam (Fig.8). Here, according to (19) and Fig.7, $dn/dx|_{x=x0} = q(x)/0 = \infty$.

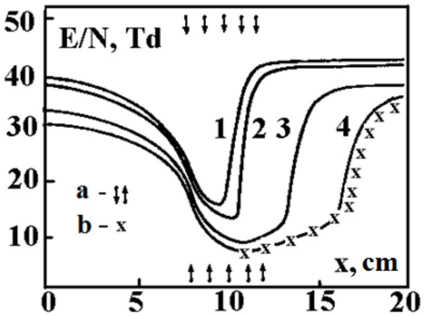

Figure 8: *E/N* profiles depending on the discharge current. a - ionizer zone, b - calculation using an 1D analytical model, see ref. in [4].

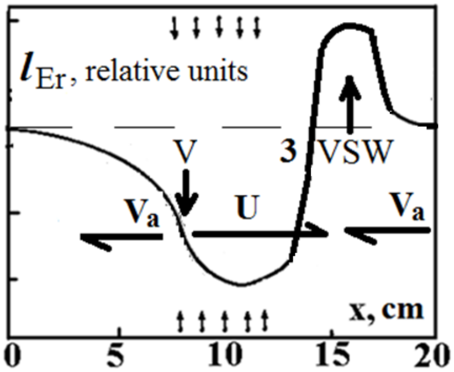

Figure 9: $\boldsymbol{l}_{Er}$ profiles depending on the parameter E/n_e (33) along a cylindrical gas-discharge tube of constant radius. a - ionizer zone; V – Vysikaylo's plasma nozzle zone; VSW – Vysikaylo's shock wave zone (gas pumping stopped – *U*); $V_a(E)$ - ambipolar plasma drift due to the different dependence of the drift velocities of electrons and ions on the *E/N* parameter [4].

In Fig.9 you can see the characteristic radial size profile - $l_{Er}(x)$ in accordance with (18) and according to curve 3 in Fig.8. In Fig.9 we see that in the region of the Vysikaylo's plasma nozzle the ambipolar flows (U and V_a) are directed in different directions from the inflection point, and in the region of the Vysikaylo's shock wave the ambipolar drifts (U and V_a) are directed towards meeting each other, which leads to the formation of a jump in plasma parameters and an increase in the characteristic radial dimensions of the luminous plasma ejected in this region onto the walls of the gas-discharge tube by ambipolar diffusion due to the space charge in this region, see references in [4]. In our numerical calculations (Fig.8) and the corresponding 3D representation (Fig.9), we can see that the inflection point is formed at the boundary of the action of the external ionizer (fast electron beam). In this numerical model, we did not take into account the flows determined by 5 and 7 terms in (16). Taking these yalens into account leads to a shift of the inflection point to the region of the positive plasma column on one side of the region of action of the fast electron beam and a displacement of the Vysikaylo's standing shock wave on the other side of the beam region (see Fig.5-7, Part 6.2 of this work).

6.2. Experimental Studies of Vysikaylo's Jumps and Plasma Nozzles in Plasma with Current

6.2.1. Introduction

In 1985 P.I. Vysikaylo theoretically predicted the existence of shock waves in collisional plasma with violation of electroneutrality and the dependence of the width of such a Vysikaylo's shock wave on the discharge current, see references in [4,20]. In [4, 17-19], we constructed the most complete 3D non-stationary Vysikaylo's perturbation theory to describe the profiles of non-stationary inhomogeneous 3D structures in gas-discharge plasma with current (hereinafter referred to as 4D theory). The small parameters of this 4D theory are: 1) the smallness of the positive ion current relative to the electron current ($\mu_+ l_E/\mu_e L \ll 1$) and the smallness of the electron energy relaxation length relative to the characteristic dimensions of the inhomogeneity – l_u/L. Here $\boldsymbol{l}_E = E/(4\pi e n_e)$ is the vectorized characteristic size of the violation of electroneutrality of plasma with current, determined by the vector parameter E/n_e [4, 17-19]. All coefficients of drift, diffusion and reaction rates are functions of the parameter E/N (N is the density of the number of neutral gas particles), in accordance with the works of Stoletov [13] and Townsend, see references in [14]. The smallness of the ratio of the ion current to the electron current (smallness of the parameter – $\mu_+ l_E/\mu_e L \ll 1$) allows solving problems with a significant violation of electrical neutrality due to the smallness of the ratio of ion mobility – μ_+ to electron mobility – μ_e, see references in [4, 17-19], in the zero approximation according to the specified parameters using the positive ion balance equation modified by me in the form [4] - (16).

According to (16), in Vysikaylo's 4D theory, which takes into account the violation of electrical neutrality, it is possible to describe the parameter profiles of 3D non-stationary inhomogeneous structures in plasma with current. Moreover, according to (16) all coefficients with vector $\boldsymbol{l}_E$ are vectors. This means that all characteristic 3D sizes of transition layers between plasma 3D structures and their characteristic 3D sizes are significantly determined by the vectorized characteristic size of the violation of electroneutrality of plasma with current – $\boldsymbol{l}_E = \boldsymbol{E}/(4\pi e n_e)$ and, therefore, are determined by the vectorized parameter E0/ne.

In Part 6.1, this perturbation theory (equation (16)) was applied to describe stationary one-dimensional parameter profiles in Vysikaylo's shock waves with violation of electroneutrality in a current-carrying plasma perturbed locally by an external ionizer. It is also shown there that the characteristic size of the Vysikaylo's shock wave in the longitudinal current direction is determined by the parameter – l_{Ex}. Based on the 4D equation (16), in Part 6.1 of this work considerations are given about the possible dependence of the width (effective radius in the case of cylindrical symmetry) of the discharge on the radial component of this parameter – $l_{Er} \sim E_{0r}/n_e$. Thus, we predicted in 1985 an inversely proportional decrease in the discharge cross section with increasing electron concentration. In Section 6.2 we present experiments in a gas discharge tube in a non-uniform high-purity nitrogen plasma (excited locally in the center of the tube by a high-energy electron beam of 100 keV). These experiments confirm the theoretical conclusions presented in Section 6.1 and provide new knowledge about the ambipolar transport processes in non-uniform simple plasma with one type of positive ions, which are not taken into account in the 1D theory.

6.2.2. Experimental Studies of Vsikaylo's Shock Waves Exist in an Electropositive Gas

Under the conditions of these experiments in plasma in nitrogen, the main processes of ambipolar transfer were gas pumping from the anode to the cathode at a speed U and ambipolar drift – V_a (the third term in (1)), caused by different dependences of the drift velocities of electrons and positive ions on the main plasma parameter – E/N [4, 17-19]. The velocity V_a in nitrogen depends on the E/N parameter, reaches, according to analytical calculations and experiments [4, 18], 70 m/s and is directed from the region of small values to the region of large values of the E/N parameter. Since V_a is directed from the Faraday dark space to the positive column, then to form regions with shock waves and Vysikaylo's plasma nozzles, where the complete ambipolar drift $U + V_a(E) \rightarrow 0$ and the role of ambipolar diffusion processes increases, the gas pumping speed should be selected from the anode to the cathode.

6.2.2.1. Experimental Setup and Method of Local Plasma Disturbance in a Gas-Discharge Tube

For an experimental study of electric field shock waves, P.I. Vysikaylo an installation was designed with longitudinal (discharge current) pumping of gas in a tube (Fig.5). The setup was a glass tube with a cross section of 3 cm^2 and a length of 45 cm. We have long used such tubes in experiments to directly prove the existence of ambipolar plasma drift – V_a, caused by nonlinearity – the difference in the dependences of the mobilities of electrons and ions on the field – $\boldsymbol{E}$, or rather on the parameter E/N, see references in [4,18]. The pumping speed U, at a gas pressure - nitrogen in the tube P = 15 Torr, could vary within 1 – 100 m/s.

The distribution of electric potential along the entire length of the tube was measured with probes soldered through ~ 3 cm (they are visible in all photographs in the form of black stripes). Typically, the gas pumping speed was chosen so that the gas did not heat up significantly ($N \approx$ const – the density of the number of gas particles in the tube).

Figure 10: Photo of a discharge in a tube in nitrogen (P=15 Torr, U = 40 m/s, I = 4mA) with a window for a beam of fast electrons in the middle. On the left is the cathode spot and Faraday dark space. $J_q = 0$.

The ignition of a stationary longitudinal (gas flow) discharge occurred when a small cathode spot was formed on the cathode and behind it, due to the ambipolar drift – V_a, a dark Faraday space was established at the cathode (Fig.10). The question of boundary conditions in a gas-discharge plasma with a cathode spot and Faraday dark space is quite complex, see references in [4,18]. Therefore, in experiments to study shock waves of the electric field (Fig.11-13) P.I. Vysikaylo proposed a method for local disturbance of the plasma concentration of a previously homogeneous extended (more than 30 cm long, Fig.10) plasma column with current in a gas-discharge tube far from the electrodes, see references in [4]. To do this, a 2x2cm2 window was located on the side surface of the tube in its center, through which a quasi-stationary beam of fast electrons with an energy of 100 keV and a current density of up to $J_q \sim 10$ μA/cm^2 was introduced into the discharge through a Mylar film. The beam carried out additional ionization of the gas and thereby created a quasi-stationary, controlled local inhomogeneity of the plasma concentration in the center of the tube in the previously homogeneous positive discharge column. After the beam was introduced, in this region and the region of perturbation relaxation, the electron concentration sharply increased and, accordingly, the electric field strength decreased (the parameter E/N decreased locally in the plasma), therefore, the average energy of electrons in the plasma decreased and the discharge glow disappeared in this region (Fig.11,12) and, accordingly, the velocity V_a sharply decreased and the plasma could change the direction of its movement. In Fig.10-12, in the center of the discharge tube one can see a window for the beam and a dark region of disturbance of the plasma column by a beam of fast electrons (Fig.11,12). Based on the contrast of the glow and the places where it is observed, one can judge the characteristic longitudinal and radial dimensions of the drift and diffusion (jumps) 3D profiles of the plasma parameters.

At this installation, experimental studies were carried out to study the self-focusing of plasma in the regions of plasma nozzles predicted by P.I. Vysikaylo, see references in [4,20]. These regions (with plasma nozzles) are located asymmetrically with respect to Vysikaylo's shock waves in inhomogeneous plasma structures (plasmoids), see references in [4,20]. We photographically recorded the 3D heterogeneity of the discharge. Let us consider the results obtained experimentally when studying the complex phenomena of interference of internal flows of inhomogeneous plasma – V_a with longitudinal flow of gas – U.

6.2.2.2. Types of Experimentally Studied Standing Vysikaylo's Shock Waves

Here we photographically demonstrate the two types predicted by P.I. Vysikaylo, shock waves of the electric field (drift jumps) with a violation of the electrical neutrality of the plasma with current and longitudinal pumping of gas, see references in [4,20] (Fig.11).

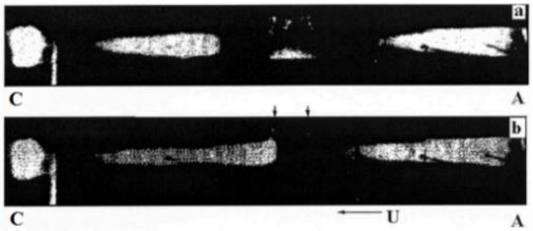

Figure 11: Discharge glow (U = 40 m/s, P = 15 torr, I = 4 mA) perturbed by a beam of fast electrons: a - case of a strong ionizer (J_q = 3 μA/cm^2) or a strong shock. The shock is outside the ionization zone; b – case of a weak ionizer. The jump is located in the region of the external ionizer. The ionizer area is indicated by arrows in the tube center.

In the first case, in Fig.6a there is a jump outside the region of the external ionizer. This corresponds to the case of a strong disturbance – a strong ionizer. In the second case, in Fig.11*b*, the Vysikaylo's shock wave is observed inside the ionizer region. This corresponds to the case of a weak ionizer [4,20]. Experiments (Fig.11) fully confirm Vysikaylo's predictions, see references in [4,20], weak and strong shock waves of Vysikaylo's electric field. Thus, in experiments we confirmed the classification of Vysikaylo's shock waves in an inhomogeneous plasma with current and gas pumping, see references in [4,20].

6.2.2.3. Photographic Evidence of the Discovery of Vysikaylo's Shock Waves and Plasma Nozzles

In experiments in 1986-1987, see references in [4], according to theory (16) [4,20], we chose: 1) the gas pumping speed – U (detailed experimental studies were carried out in high-purity nitrogen), 2) the density of the beam of fast electrons, locally increasing the plasma concentration, and 3) the magnitude of the discharge current – I, conditions were created under which, according to the model [4,17-19], the total velocity of the inhomogeneous plasma $U + V_a$ in the positive column and in the area of influence of the external ionizer had opposite directions and thus an ambipolar drift – V_a+U cumulated (collapsed) plasma energy-mass-impulse flows (**EMIF**). This can be achieved according to the model [4] by pumping gas from the anode.

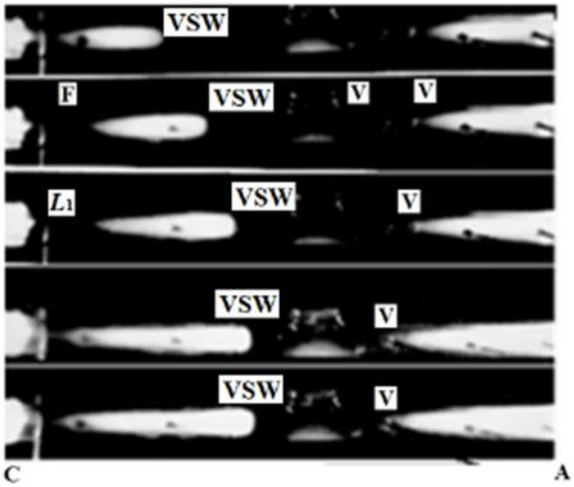

Figure 12: This is photographic evidence of the formation of Vysikaylo's shock waves – VSW and Vysikaylo's plasma nozzles – V (in plasma with current). U = 40 m/s (from A to C), J_q = 3 μA/cm2, Density *I* varies from 0.33 mA/cm^2 to 1.52 mA/cm^2. F – Faraday dark space. L_1 is Vysikaylo's cumulation point between positively charged luminous plasma structures (cathode spot and positive column).

As we established in theory [4], disturbance of the plasma column by a local additional ionizer (a beam of fast electrons) should lead to the formation of asymmetric profiles of plasma parameters. According to the 1D theory [4], on one side of the disturbance a Vysikaylo's shock wave is formed, and on the other side of the external disturbance a Vysikaylo's plasma nozzle should be formed. In the experiments, we created conditions under which, in regions perturbed by an external ionizer, standing Vysikaylo's shock waves of the electric field arose and, on the opposite side of the Vysikaylo's shock wave and external disturbance (windows for the beam), plasma 3D structures self-formed in region V – Vysikaylo's plasma nozzles (Fig.12). These Vysikaylo's plasma nozzles are similar to Laval's nozzles in conventional gas dynamics [4]. These [4] asymmetric luminescence profiles are observed in experiments (Fig.11,12). The Vysikaylo's 3D plasma nozzle is formed behind a window for a beam of high-energy electrons (Fig11,12) – this area is marked with the letter V.

Fig.12 shows 5 photographs of the discharge depending on the discharge current, varying five times, from 0.33 to 1.52 mA/cm^2. From a comparison of photographs (Fig.12) it is clear that with increasing discharge current:

1) The dimensions of the luminous plasmoids longitudinal to the current increase, while

2) The left glowing plasmoid (towards the anode – A) ends with the Vysikaylo's shock wave. The Vysikaylo's shock wave has an elliptical shape;

3) The shape of the Vysikaylo's shock wave and its width depend on the discharge current, in accordance with the theory, see references in [4,20]. At the maximum discharge current, the width of the Vysikaylo's shock wave in these experiments reaches l_{Ex}≈1.5 cm and its shape becomes elliptical (Fig.12, Photo 4,5). This indicates the generation of dynamic surface tension in 3D plasma luminous structures with a space charge;

4) The intensity of the glow of the Vysikaylo's shock wave increases significantly with increasing discharge current, which indicates an increase in the *E/N* parameter in the shock wave (Fig.12, region – VSW), as predicted in theory, see references in [4,20]. An increase in the *E/N* parameter leads to an increase in the space charge and the ejection of plasma particles onto the walls of the tube, which leads to an increase in the effective cross section of the discharge in the region of the Vysikaylo's shock wave (Fig.8,9);

5) Behind the window area for introducing a beam of high-energy electrons, the formation of a 3D Vysikaylo's plasma nozzle is observed, approaching the window with increasing discharge current – *I*;

6) The radial cross section of the discharge in region V of the Vysikaylo's plasma nozzle is many times smaller than the radial cross section in the shock wave of the electric field (Fig.12, VSW).

7) With increasing discharge current, the areas of formation of shock waves of the electric field and the areas of Vysikaylo's plasma nozzles approach the area of action of the high-energy electron beam (Fig.12). This indicates that the role of ambipolar: recombination flux and ambipolar diffusion - terms 5 and 7 in (16), caused by the violation of electrical neutrality in plasma with current, decreases with increasing current. The role of these members requires further research.

8) With increasing discharge current, the areas of the positive column in the inhomogeneous plasma with current expand and, as a result, an electric cord is formed - an electric arc with cylindrical symmetry.

Experiments (Fig.11,12) clearly prove the presence of the processes of radial cumulation and dissipation predicted by us, determined by the parameter E/n_e or the vector lE. These self-cumulation processes determine the radial sizes of plasmoids according to (16) due to changes in the *E/N* parameter in an inhomogeneous plasma with current. These 3D phenomena of a sharp change in the discharge cross-section occur without the influence of a magnetic field and without the use of special Loval's nozzles. In inhomogeneous plasma with current, self-formation of Vysikaylo's plasma nozzles occurs due to the cumulation of plasma flows.

6.2.2.4. Probe Studies of *E/N* Profiles in Standing Vysikaylo's Shock Waves

To obtain the statistical profile of the field – *E*(*x*) in the Vysikaylo's shock wave region, we used a double probe. We moved the probe from one experiment to another at established discharge parameters, gas pumping speed and high-energy electron beam current. This is how *E*(*x*) measurements took place, see references in [4].

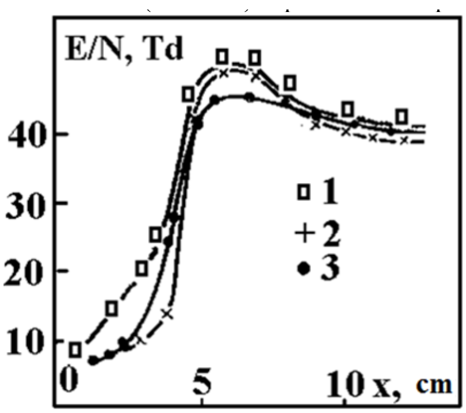

Figure 13: The distribution of reduced electric field strength measured by a double probe (E/N(x) in Td) in the shock (standing Vysikaylo's shock wave) P = 15 Torr, 1 – I = 4 mA, U = 80 m/s (A → C); 2 – I = 1.5 mA, U = 40 m/s (A → C); 3 – I = 1.0 mA, U = 40 m/s (A → C).

The E/N parameter profiles obtained as a result of (about 30) experiments are presented in Fig.13 in the form of three curves. From Fig.13 it is clear that the parameter *E/N* in the shock is significantly ~ 20% higher than its value in a homogeneous unperturbed positive plasma column (*E/N* ~ 40 Td). This is a 3D effect. It is associated with a significant difference between 3D phenomena in electric field shock waves and phenomena in Mach's shock waves. This is due to the generation of electric fields transverse to the current in the Vysikaylo's shock wave and the release of positive ions onto the walls of the tube. The more intense removal of plasma in the direction transverse to the current and its destruction on the walls of the tube leads to an increase in the *E/N* parameter in the zone of the Vysikaylo's shock wave, stopped by gas pumping, see references in [4].

6.2.3. Studies of Vysikaylo's Cumulative - Dissipative Structures in Plasma with Current

Here the author for the first time fully presented his convincing theoretical (Fig.8 and Fig.9, constructed according to equation (16) [4,17]) and experimental confirmation of theory (16) (Fig.11-13, see links in [4,20]) evidence of the formation and long-term existence of Vysikaylo's standing shock waves of the electric field and Vysikaylo's plasma nozzles. In this case, we specially stopped these waves by pumping gas at a speed – U = const, directed from the anode to the cathode [4,18]. The velocity of ambipolar drift (due to the difference in the dependences of the mobilities of electrons and positive ions on the *E/N* parameter [4,18]) – V_a, in nitrogen plasma (as in a number of other gases [4,18]), is directed from the cathode to the anode (from small values of the *E/N* parameter to large values of this parameter), see references in [4,18]. 3D interference and diffraction of the electric field strength (according to the discharge glow and the profile measured by double probes) in an inhomogeneous plasma with current, due to two oppositely directed ambipolar drifts: 1) V_a, and 2) gas pumping – U, photographed and studied depending on the intensity of the beam of high-energy electrons (Fig.11), the magnitude of the discharge current (Fig.7) and the gas pumping speed (Fig.12).

Let us detail our results. According to our theory and our experiments (most fully presented in this work), see references in [4, 17-20], pumping gas – U stops the shock wave of the electric field in an inhomogeneous plasma with current and interfering with it (with V_a and the electric field – E) leads to the formation of:
1) 3D Vysikaylo's plasma nozzle (region V in Fig.8-9 and Fig.11-13) - an analogue of the Laval nozzle. In this region, ambipolar drifts are directed in opposite directions at the inflection point of the concentration profile of charged plasma particles. No shock wave is formed in this region;
2) 3D standing Vysikaylo's shock wave of the electric field, both in the ionizer zone - a weak ionizer, and in this zone – a strong ionizer (Fig.11). In the region of the Vysikaylo's shock wave, ambipolar drifts are directed toward meeting each other. This is the condition for the survival of the electric field shock wave. The Vysikaylo's shock wave expands in the radial direction due to the space charge self-focusing (in the longitudinal current direction) in this area – VSW (Fig.9 – theory (16) and Fig.12 – experiment, see references in [4,20]);
3) 3D transient profiles of inhomogeneous plasma parameters with their deep 3D modulation (Fig.8-9 and Fig.11-13) in 3D space. 3D modulation of plasma parameters is caused by interference and diffraction of the electric field in an inhomogeneous plasma with current. The characteristic dimensions of transition profiles are significantly determined by the processes of ambipolar transfer (various drifts and diffusions) and plasma-chemical reactions (recombination, electron attachment in electronegative gases, etc.). By studying the glow profiles of inhomogeneous plasma with current, it is possible to determine the effective processes of plasma transfer, birth and death [4, !7-19];
4) 3D pulsations in the space of longitudinal - Ex and transverse electric fields – E_r (Fig.8-9 – theory (16) and Fig.11-13 – experiment);
5) Two luminous plasma structures in region V (Fig.12, photo 1,2). Luminous structures appear at low currents. These structures are similar to cathode spots and have characteristic dimensions close to the dimensions of the cathode spot, which indicates a normal current density to these positively charged structures. As the discharge current increases (Fig.12), the luminous structures approach the area of action of the high-energy beam and, at high currents, merge with the plasma nozzle in region V (Fig.12 photo 5);
6) Shift of region V of the Vysikaylo's plasma nozzle (Fig.12) from the area of action of the high-energy beam towards the anode. (With an increase in the discharge current, region V from the area of action of the high-energy electron beam moves towards the cathode).

The generation of luminous plasma structures in the region of the Vysikaylo's plasma nozzle at low currents turned out to be an unexpected phenomenon for us. All other phenomena, electric field pulsations in an inhomogeneous plasma with current, were predicted by us theoretically in a one-dimensional approximation, see references in [4, 20]. The 3D cumulative and dissipative phenomena we predicted on the basis of (1) (Fig.9), leading to the formation of cumulative-dissipative 3D structures (CDS) and pulsations of characteristic sizes and electric field strength – E, were confirmed in our experiments (Fig.11-13). Ambipolar drifts [4, 17-19] (and ambipolar anti-diffusions [19]) are responsible for cumulative phenomena in plasma with current, and ambipolar diffusions are responsible for dissipation [19]. In this work, we experimentally proved the existence of Vysikaylo's cumulative-dissipative structures (CDS) [19] in plasma with current.

Our results prove that the electric field in a plasma with current is a full-fledged third (vector) component even in a simple plasma (with one type of ions) and to describe the interference and diffraction of the electric field in an inhomogeneous plasma it is necessary to use the 3D Poisson equation or the 4D Vysikaylo's model in form (1) [4,17-19], and not be limited to the neutral approximation.

Unlike Kolmogorov-Turing-Prigogine's dissipative structures, where the main transfer processes are diffusion processes with scalar diffusion coefficients, in Vysikaylo's plasma CDS the main transfer processes are convective processes – V_a, U (see for more details [4,17-19]); processes of ambipolar diffusions with vector coefficients (see [4,19] for more details), etc. [17-19]. We have proven theoretically and experimentally (Fig.11-13) that the cumulation of the electric field can lead to local self-focusing of a space charge in a current-carrying plasma, the formation of surface dynamic tension of plasmoids (Fig.12), the formation of shock waves of the electric field, and the formation of Vysikaylo's plasma nozzles – analogues to Laval's nozzles, as well as the formation of cumulative jets of both electrons and positive ions. Positive ions can cumulate on cumulating electron flows, i.e. ambipolar bi-cumulation of the plasma as a whole can be realized [2,4,5].

Before 1985, certain differences between finite-dimensional 3D electric field shock waves (VSW regions, Fig.9 and Fig.12) and Mach's shock waves were obvious to the author. These differences (due to the interference of internal ambipolar drift with the pumping of neutral gas in an inhomogeneous plasma) are associated with the generation of electric fields transverse to the current and with the local cumulation of space charge during 3D jumps in plasma parameters depending on the current value. In Vysikaylo's shock waves, monolayers with a positive charge are formed, rather than double layers, as is usually assumed in the literature [20]. (The second negative layer is carried by electrons far beyond the boundaries of the problem).

In 3D mono-layers of space charge, profiles of the E/N parameter are formed, in which inhomogeneous heating of charged plasma particles occurs. The cumulation of space charge can be carried out by ambipolar drift of one nature or another, both in the longitudinal direction with respect to the current, and in directions orthogonal (transverse) to the current, which leads to compression of the columns of positive discharges. Photographs (glow) of quasi-stationary phenomena of interference and diffraction of the electric field – E, caused by convective and diffusion (cumulative and dissipative) processes in an inhomogeneous plasma with current, taken by me and my co-authors (see references in [4]), were obtained and published by us already in 1986-1987 (Fig.10-13). [https://www.mathnet.ru/links/71165a7c62aada05aa9995922e504d54/pjtf234.pdf].

The most complete list of ambipolar drifts studied by us is presented in [2,4,17-19]. In [19], we compared three types of ambipolar diffusions: 1) Schottky's; 2) Vysikaylo-Poisson's; and 3) Vysikaylo-Euler's. In this work, attention is drawn to two more types of ambipolar transfers: 1) ambipolar diffusion due to the violation of electrical neutrality and the presence of gas pumping – the 5th term in (16) and 2) recombination drift - the 7th term in (16), caused by differences in the concentrations of positive ions and electrons. We have not studied these terms in detail in experiments and theory. Numerical calculations shown in Fig.8 and Fig.9 were carried out without taking these members into account. However, their importance in our experiments was manifested in a significant displacement of the Vysikaylo's plasma nozzle (region V, Fig.12) from the area of action of the high-energy electron beam. At low discharge currents, these ambipolar transfer processes play a more significant role (Fig.12, photo 1,2) than at high currents (Fig.12, photo 5).

As our studies have shown, space charge cumulation can be of three types: 1) spherical; 2) cylindrical, conical; 3) flat in the form of layers, shells, etc. (Fig.11,12) [1,2,4,5]. In accordance with the types of cumulation, the corresponding types of 3D shock waves of the electric field (parameter E/N) and 3D Vysikaylo's plasma nozzles with characteristic sizes determined by the parameters E/N and E/n_e arise.

Perturbation theory, which takes into account the violation of electrical neutrality, was initially formulated by me for one-dimensional non-stationary problems (with spherical, cylindrical and flat geometry), see references in [4]. Already at this stage, this theory made it possible to explain the experimentally observed Pekarik's effect: opposite directions of group and phase velocities of traveling striations (traveling shock waves of the electric field) in a plasma with current. This phenomenon is associated with the significant role of the second term in (16) [19]. The bi-cumulation of positive ion fluxes on a cumulative electron jet (towards the anode) in the region of a positively charged cathode spot was discovered and explained [2]. Based on this model, the reverse motion of the cathode spot (a positively charged structure that cumulates free electrons), discovered by Stark in 1903, was explained in [2]. We also, on the basis of Vysikaylo's perturbation theory [17-19], explained other cumulation phenomena in cumulative-dissipative structures discovered by Vysikaylo, see references in [2,4,5,11].

4D theory - (16) for the first time allows us to explain all the 3D phenomena that we observed in the experiments presented in Fig.11-13. In these experiments, a standing Vysikaylo's shock wave in an inhomogeneous plasma with current is formed due to ambipolar drift – V_a (due to different dependences of the drift velocities of electrons and positive ions on the E/N parameter [19]), propagating from the dark Faraday space to the anode, and pumping gas – U (positive ions frozen into the gas flow) from the anode to the cathode. In this case, the ambipolar flows ($V_a \rightarrow \leftarrow U$) collapse (collide). From opposite sides, they cumulate flows of ambipolar inhomogeneous plasma to the space charge layer and thereby form a standing shock wave with a space charge in the plasma with current, see references in [4,17], (Fig.12). We applied 4D perturbation theory (16) [17] to describe the behavior of lightning, stationary (Faraday et al.) and moving (Pekarik's effect and Gunn's effect) strata, plasma tails behind meteoroids, electric field shock waves and Vysikaylo's plasma nozzles, previously predicted by the author (Fig.12). Our experiments confirm the discovery of 3D electric field shock waves, which, due to space charge, tend to dissipate (expand to form narrow shells or layers that become more extensive laterally) and self-focus (to become narrower in the transverse direction) in an inhomogeneous plasma with current. The phenomena of increase and decrease in the characteristic dimensions of the violation of electrical neutrality in the discharge are described by the vectorized parameter $\boldsymbol{E}/n_e$ according to (16).

In the general case, the formation of 3D standing Vysikaylo's shock waves can be caused by the interaction of various ambipolar plasma flows directed towards each other (Fig.9, VSW region). This main criterion for the survival of the Vysikaylo's shock wave corresponds to the formation and existence of Mach's shock waves. If there is a point in the plasma where effective ambipolar flows are directed in different directions (← →), then in the area of this point a Vysikaylo's plasma nozzle is formed (Fig.9 and Fig.12, region V) - an analogue of the Laval's nozzle.

The author in his works proves that similar (Fig.8-9 and Fig.11-13) 3D interference and diffraction of the electric field arise when other ambipolar drifts interact with each other in an inhomogeneous plasma with current. Moreover, these ambipolar drifts and ambipolar diffusions determine the 3D characteristic sizes of cumulative-dissipative structures and 3D transition profiles between them in plasma with current (Fig.9) [4,11,17-19,28].

In full accordance with the 4D theory (16), see references in [4,20], as experiments have shown (Fig.11,12), on one side of the local ionizer in a current-carrying plasma, a Vysikaylo's shock wave profile is formed (Fig.9), where plasma flows expand in the transverse direction to the current. On the opposite side of the shock wave, a Vysikaylo's plasma nozzle is formed, in which the derivative of the electron concentration tends to ∞ and here plasma flows cumulate in the transverse direction to the current (Fig.9). An external local ionizer in a plasma (with current) plays the role of a plunger (piston), simultaneously forming inhomogeneous profiles of plasma parameters that are asymmetric with respect to the local disturbance. This asymmetry of shock waves and Vysikaylo's plasma nozzles (relative to each other) allows us to visually determine in plasma with current: 1) the directions of flows of charged particles (thus determining the analogues of the cathode and anode, respectively), 2) the direction of growth of the E/N parameter and 3) determining points, lines and planes of Vysikaylo's cumulation (analogues of the Lagrange's libration points – $L_{1\text{-}3}$, discovered by Euler in 1767 between Jupiter and the Sun), see [5].

In the general case, if the cumulation of the space charge occurs in the direction of the current, then its expansion (this is indicated by the glow of this region, Fig.12) occurs in orthogonal directions. This leads to the formation of narrow shells with characteristic dimensions – l_{Er} or self-forming Vysikaylo's plasma nozzles. Conversely, if cumulation occurs in a direction transverse to the current, as in linear lightning, in a plasma tail behind meteoroids, or in a jet from the M87 galaxy (Fig.14), then energy-mass-pulse flows sputtering (or scattering, including in the form of a beam of charged particles) occurs in the longitudinal direction to the current [5,11].

In Fig.11,12 show quasi-stationary inhomogeneous discharges (perturbed locally by a beam of fast electrons) with gas pumping. In this case, from the profiles and shape of the inhomogeneous profiles, we can determine the direction of the global current. In Fig. 14a,b shows the glow profiles of inhomogeneous non-stationary (pulsed) plasma CDS in electronegative gas (air). In air plasma, the role of negative ions should be taken into account: the rate of electron attachment to oxygen molecules, the rate of destruction of negative ions, etc. However, we see that in these structures in the air, dynamic surface tension is formed. The dynamic surface tension of such non-uniform CDS is also determined by the breakdown of electrical neutrality, the generation of electric fields, and the formation of electric field shock waves. We have just begun to study these processes in our works, and here we have to figure out where the current flows. For such structures, oscillatory processes or pulsating current are possible. A. Vlasov discussed such pulsations.

As for determining the direction of the global current in the stationary CDS presented in Fig.14c (according to their visualized glow, their lifetime is more than 4.9 thousand years), then here we should use the knowledge we have acquired about CDS.

Figure 14: This is a demonstration of dynamic surface tension, which accumulates energy in plasmoids:
a) Beaded lightning in the Earth's atmosphere, L_1 – Vysikaylo's cumulation points [5];
b) The sprite at altitudes of 50 - 90 km.
c) The central region of the M 87 galaxy with an active nucleus. Jet size ~ 1.5 kpc. We observe jet stratification and formation of

cumulation regions. Hubble Telescope (NASA).

The author claims that all 3D plasma structures are formed with the participation of shock waves of the electric field (*E/N* parameter). These waves perform the function of skin, fur coat or cover for plasma structures of various geometries. Shock waves of the electric field cumulate (focus) electrons into positively charged structures, form cumulative jets from them and more slowly spray positive ions generated in the CDS.

In local phenomena in plasma with current, it is not so much the magnitude of the electric field – *E* – that is important, but rather the value of the parameter *E/N*. This was pointed out by Stoletov (*E/P* parameter), and then by Townsend, who proved in experiments that all diffusion coefficients, drifts and reaction rates are determined by the *E/N* parameter, see references in [4]. Our works note the importance of the vectors *E/N* and E/ne, see (16) [4,17-19]. This achievement in gas-discharge plasma (following from Paschen's integral law) has not yet been properly recognized by astrophysicists. The author states in his works that similar cumulative and dissipative phenomena with current are realized not only in laboratory gas-discharge plasma (Fig.9. and Fig.11-13), but also in many structures in Space (Fig.14). In words, we do not were the first in such a formulation of the problem for inhomogeneous plasma in the heliosphere.

According to Parker [28] (his work is cited by all astrophysicists who study the heliosphere), the first clear statement that something other than light comes to the Earth from the Sun was made in 1896 by the Norwegian physicist Christian Olaf Bernhard Birkeland. He proposed that the aurora could be created by electrically charged "corpuscular rays" ejected from the Sun and focused (cumulated) by the Earth's magnetic field near the poles. He came to this conclusion based on the fact that auroras are very similar to the electrical discharge in the then recently invented gas-discharge tubes that generate streams of charged particles ("cathode rays"). And here Birkeland or Parker could apply the Generalized Mathematical Transposition (transfer) Method (GMTM) of Newton (Hooke): "Everything that happens on Earth is similar to phenomena in the Cosmos." In principle, this method was also used by Eratosthenes (Eratosthenes of Cyrene; ʼΕρατοσθένης ὁ Κυρηναῖος) (about 276 BC - 194 BC, Cyrene – Alexandria), an ancient Greek scientist and poet. Using this method, he determined the radius of the Earth. In the same work, he considered astronomical problems on the basis of this method.

Based on the paradigm: "Everything that happens on Earth is similar to phenomena in Space" and on the basis of knowledge about the properties of the plasma of a laboratory gas discharge between the anode and the cathode, Birkeland or Parker could explain all the "mysterious" phenomena in the heliosphere and ionosphere of the Earth associated with the weak solar wind (SV). To do this, they needed to discover and verify the mechanism of a constant global current in the entire heliosphere between the positively charged Sun and the negatively charged Earth, and not get carried away by turbulence and the magnetic field. We proposed such a mechanism, see references in [11]. This mechanism is similar to the mechanism in a gas discharge, and it maintains (in dynamics) the positive charge of the Sun at 1400 C [11].

As evidence of the movement of charged particles from the Sun in the 50s, Ludwig F. Biermann from the University of Göttingen cites his calculations. These calculations showed that the pressure of sunlight is not enough to explain the rapid outflow of cometary gases from the Sun. He showed that the only type of solar radiation that could explain the repulsion of cometary tails is the flow of corpuscles from the Sun. Birman discovered important facts that influence the solution to the question of how this solar corpuscular radiation arises. Until this time, hypotheses proceeded mainly from two possibilities: either the corpuscles were emitted by solar flares or they were ejected in the form of streams from sunspots. But Birman's arguments made it clear that corpuscular radiation could not come only in bursts or isolated streams. Comet tails showed that the radiation of corpuscles spreads continuously from the Sun in all directions. This is a weak solar wind. If the charge of the Sun is positive and its charge is about 1,400 C, then protons, alpha particles and all ions observed in the weak solar wind will be accelerated from the Sun [11].

The presence of positive iron ions in the solar wind and all its properties (in particular, acceleration away from the Sun) prove to us the existence of a global current in an inhomogeneous gas-discharge plasma throughout the heliosphere [11]. The heterogeneity of the heliosphere and its properties are significantly determined by the dependence of the particle number density – N(r) on the distance to the Sun, see references in [11]. The negative charge of the Earth of 500 kC was known to Lomonosov. Based on the model of the positive charge of stars [26,29], Eddington analytically estimated the positive charge of the Sun to be 300 C [30]. Such a charge is sufficient for the Coulomb reflection from the positively charged Sun of not only protons, but also helium ions [11], but for the reflection of positive Fe+6 ions observed in the solar wind, see references in [11], the charge of the Sun should be of the order of 1400 C [11]. Based on data obtained by the Parker's probe, Helikas estimated the profile of changes in the effective charge of the heliosphere from 200 C near the Sun to 500 C in Earth's orbit. However, this positive charge of the Sun and the positive charge of the heliosphere is not enough to explain the presence of Fe+6 ions in the solar wind, see references in [11]. We in [11], based on the types of positive ions (in experiments, see references in [11]) in the solar wind (between the Sun and the Earth at point L2, discovered by Euler in 1767 in Russia), for the first time estimated the charge of the Sun at 1400 C [11] and explained the difference between our results and those of Helikas, see [11]. In [11], we examined the interference of gravitational and electric potentials in the inhomogeneous heliosphere with current, caused by the difference in the fluxes of electrons escaping from the Sun and the fluxes of electrons returning to the positively charged Sun. The difference between these fluxes determines the flux of positive ions from the positively charged Sun.

This stream of positive ions is formed from positive ions for which the gravitational force is less than the force of Coulomb repulsion from the Sun. This is how a weak spherically symmetric solar wind is formed, according to [11]. Taking into account the global current in the inhomogeneous (with a sharp decrease in gas density – $N(r)$ from 10^{17} cm^{-3} at the surface of the Sun to 2.5 cm^{-3} in the region of the Earth's orbit, see more details [11]) heliosphere between the positively charged Sun and the negatively charged Earth allows us to explain all phenomena caused by weak solar wind [11]. In this case, the Sun is an analogue of the anode; negatively charged Earth – cathode; a positively charged heliosphere, inhomogeneous due to N(r), is an analogue of a positive column in a gas-discharge plasma; and the positively charged ionosphere of the Earth is an analogue of a positively charged cathode spot, cumulating free electrons and positive ions to the magnetic poles of the negatively charged Earth, see references in [4,5,11].

According to [11], it is possible that a standing shock wave of the electric field is formed in the region of the Earth's orbit. In this region, the parameter $E/N(r)$ in the heliosphere reaches its maximum value due to a sharper drop in the concentration of particles – $N(r)$ from the distance to the Sun than the electric field – $E(r)\sim 1/r^2$ [11]. Further, the Earth's orbit in the heliosphere $N(r)$ remains constant, see references in [11], with increasing distance to the Sun, and the parameter $E/N(r)$ decreases as $1/r^2$. This bell-shaped geometry of the $E/N(r)$ parameter can lead to the formation of a standing shock wave of the electric field in the region of the Earth's orbit. In this region, ambipolar drifts from and to the Sun are directed toward meeting each other [11], which is a condition for the survival of a standing Vysikaylo's shock wave of electric field [4].

The results obtained in [11] allow us to assert that corpuscles (positive ions and electrons) in plasma with current in Space behave in a similar way as in laboratory plasma with current. In the heliosphere with current, as in a laboratory discharge, the formation of a compensatory negatively charged second layer does not occur [11]. Streams of charged particles and electric fields form cumulative-dissipative Vysikaylo's structures (shock waves; plasma nozzles; Vysikaylo-Euler's cumulation-libration points, lines and shells, etc. [5]). The presence of similar plasma 3D structures with sizes ranging from 1 m in the Earth's atmosphere (Fig.14a) to 10^{26} m (Fig.14c) indicates the presence of global electric currents both in the heliosphere and in Space (Fig.14c). The structure in Fig.14c cannot be a neutral gas emission. Only a positively charged jet that focuses and accelerates electrons into the black hole at the center of M87 can exist for many millennia and supply high-energy electrons to the black hole to compensate for its space charge [1]. We will carry out detailed calculations for jet M 87 in the next work, based on GMTM (Eratosthenes).

7. Conclusions

In our works, see references in [1,2,4,5], we were the first to theoretically and experimentally study the processes of: 1) ambipolar transfer due to violation of electrical neutrality and 2) interference and diffraction of electric fields when pumping gas in an inhomogeneous plasma with current. In this work, the author for the first time, using (16), studied the 3D co-organization of opposite flows of electrons and positive ions, taking into account internal electric fields as the third component of a current-carrying plasma. Here we did not take into account the inertial and torsion fields acting on charged particles with mass. We noted what processes of ambipolar transfer this leads to in [19]. The generation of a magnetic field in a plasma with a current confirms that the electric field is similar to the third component in a simple plasma with a current.

Our experiments clearly prove that we are indeed observing three-dimensional electric field shock waves (analogues of Mach's shock waves) and self-organizing three-dimensional plasma nozzles (analogs of Laval nozzles), predicted by P.I. Vysikaylo. Experiments confirm that in [4,17-19] we constructed the most complete 4D perturbation theory (16) to describe inhomogeneous and non-stationary Vysikaylo's cumulative-dissipative structures (3D CDS) in plasma with current, taking into account the violation of electrical neutrality. The main achievement of this theory – (16), which takes into account the violation of electrical neutrality, is the establishment of a significant dependence of all the effective coefficients of ambipolar transfers (drifts and diffusions) that we have discovered on the 3D vectorized characteristic size of the violation of electrical neutrality – $\boldsymbol{l}_E$ (parameter E/n_e) [4, 17-19].

In [4,17-19] we proposed the most complete perturbation theory to describe the processes of ambipolar transport in inhomogeneous structures in plasma with current. This theory is devoid of all the shortcomings noted by A.A. Vlasov about inferior theories, see references in [3,4,17-19].

Theoretical results obtained by modeling shock waves of the electric field (E/N), discovered by the author in experiments with laboratory plasma (Fig.11-13), see references in [1,2,4,5], turned out to be useful for the development of models describing the cumulative dissipative plasma phenomena during the destruction of meteoroids by a beam of high-energy electrons, phenomena in the heliosphere, atmosphere and ionosphere of the Earth, since the Earth has a negative charge of about 500,000 C, and the Sun is positively charged at a level of 1400 C [11]. The author hopes that equation (16) will be useful for the analytical description of cumulative formations in the intergalactic space of the M 87 galaxy. And with this we will once again confirm the Eratosthenes' idea.

The author was the first to study in detail self-forming electric field shock waves arising due to a violation of the electrical neutrality of plasma with current, and plasma nozzles - analogues of Laval's nozzles. Such cumulative-dissipative structures discovered by the author are of great scientific and practical interest for astrophysics and gas-discharge plasma (from the Earth's atmosphere to intergalactic lightning).

In this work we investigated theoretically and experimentally how an electric field acts on matter, and matter (charged particles) acts on the 3D distribution of the electric field in space. The author proves that the violation of electrical neutrality of plasma (charged particles) and the processes of cumulation and dissipation permeate structures from femto sizes (10^{-15} m) to the size of intergalactic lightning (10^{26} m) (Fig.14). In this paper (based on [2,4,5,9,11,13--20,22-26]) we examined in detail quasi-stationary self-forming profiles in an inhomogeneous plasma with current and classified them into drift profiles and diffusion jumps (the Vysikaylo's shock waves of electric field caused by the violation of electroneutrality). The author considered quantum-Coulomb pulsars in nano- and femto-worlds in [31,32], and in the meso-world protecting the Earth from meteoroids in [33]. The fundamentals of the theory of Coulomb pulsars in quantum stars are discussed in [1]. The author hopes that by taking into account electric fields, one can get to Einstein's Λ-term.

Author Declarations

Conflict of Interest

The author has no conflicts to disclose.

Author Contributions

Vysikaylo P.I. did everything self.

Data Availability

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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